Plant Factory Using Artificial Light

Adapting to Environmental Disruption and Clues to Agricultural Innovation

Edited by
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Contributors

Masakazu Anpo

Masakazu Anpo Department of Applied Chemistry, Graduate School of Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka, Japan; State Key Laboratory of Photocatalysis on Energy and Environment, Fuzhou University, Fuzhou, Fujian, P. R. China

Fiona E. Belbin

Fiona E. Belbin School of Biological Sciences, University of Bristol, Bristol, United Kingdom

Jasper den Besten

Jasper den Besten Horticulture Department, HAS University of Applied Sciences, 's-Hertogenbosch, The Netherlands

Nicholas E. Comben

Nicholas E. Comben School of Biological Sciences, University of Bristol, Bristol, United Kingdom

Antony N. Dodd

Antony N. Dodd School of Biological Sciences, University of Bristol, Bristol, United Kingdom

Wei Fang

Wei Fang Department of Bio-Industrial Mechatronics Engineering, National Taiwan University, Taipei, Taiwan (R.O.C.)

Masato Endo

Masato Endo Department of Marine Biosciences, Tokyo University of Marine Science and Technology, Tokyo, Japan

Donald P. Fraser

Donald P. Fraser School of Biological Sciences, University of Bristol, Bristol, United Kingdom

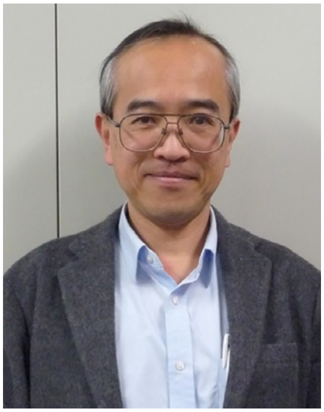
Hirokazu Fukuda

Hirokazu Fukuda Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, Sakai, Japan

Hajime Furukawa

Hajime Furukawa Graduate School of Life and Enviromental Science, Osaka prefecture University, Sakai, Japan

Naoya Fukuda



Naoya Fukuda Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki Prefecture, Japan

Atsushi Hashimoto

Atsushi Hashimoto Graduate School of Bioresources, Mie University, Tsu, Mie, Japan

Eric Haubruge

Eric Haubruge University of Liège, Liège, Belgium

Yu Horiuchi

Yu Horiuchi Department of Applied Chemistry, Graduate School of Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka, Japan

Hiromichi Itoh

Hiromichi Itoh Department of Agricultural Engineering and Socio-Economics, Graduate School of Agricultural Science, Kobe University, Japan

Koji Iwamura Osaka Prefecture University, Graduate School of Humanities and Sustainable System Science, Dept. of Sustainable System Science, Sakai, Japan

R.J.P. Janssen

R.J.P. Janssen Horticulture LED Solutions, Signify, High Tech Campus 7, Eindhoven, The Netherlands

Takaharu Kameoka

Takaharu Kameoka Graduate School of Bioresources, Mie University, Tsu, Mie, Japan

Masataka Kataoka Graduate School of Comprehensive Rehabilitation, Osaka Prefecture University, Habikino, Osaka, Japan

M.P.C.M. Krijn

M.P.C.M. Krijn Philips Lighting Research; Lighting Research, Signify, High Tech Campus 7, Eindhoven, The Netherlands

Yoshiaki Kitaya

Yoshiaki Kitaya Osaka Prefecture University, Osaka, Japan

Chieri Kubota

Chieri Kubota The Ohio State University, Columbus, OH, United States

Yi-Chueh Lin

Yi-Chueh Lin Industry technology Research Institute (ITRI)/Taiwan Plant factory Industry Development Association, Hsinchu, Taiwan

Sara Masoud

Sara Masoud The University of Arizona, Tucson, AZ, United States

Masaya Matsuoka

Masaya Matsuoka Department of Applied Chemistry, Graduate School of Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka, Japan

Chao Meng

Chao Meng Valdosta State University, Valdosta, GA, United States

Shogo Moriyuki

Shogo Moriyuki Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, Osaka, Japan

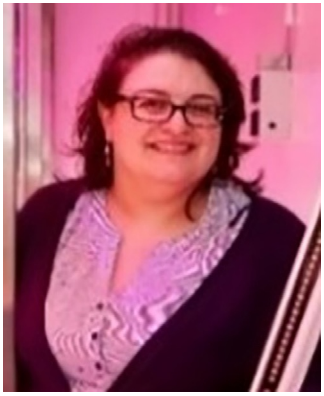
Bach Kim Nguyen

Bach Kim Nguyen University of Liège, Liège, Belgium

Kenji Nakamura

Kenji Nakamura Environment Monitoring Dept., ESPECMIC Corp., Neyagawa, Japan

Celine C.S. Nicole



Celine C.S. Nicole Philips Lighting Research, Eindhoven, The Netherlands

Yoshikazu Nishida

Yoshikazu Nishida Itoh Denki Co., Ltd. Plant Factory R&D Department, 1146-2 Asatsuma-cho, Kasai-shi, Hyogo, Japan

Yoshito Oka

Yoshito Oka Basic Forestry and Proteomics Research Center, Fujian Agriculture and Forestry University, Fuzhou, China

Nobuaki Okada Itoh Denki Co., Ltd. Plant Factory R&D Department, 1146-2 Asatsuma-cho, Kasai-shi, Hyogo, Japan

Toichi Ogura Sanshin Metal Working Co. Ltd., Osaka, Japan

Kuniharu Okuda

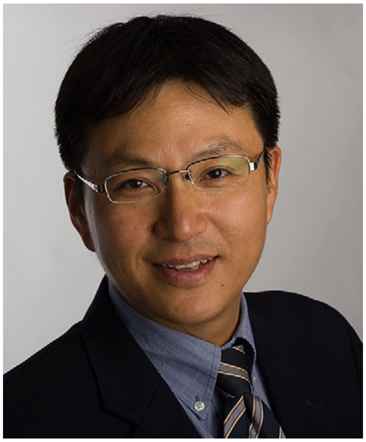
Kuniharu Okuda Graduate School of Comprehensive Rehabilitation, Osaka Prefecture University, Habikino, Osaka, Japan

Satoshi Okahara Graduate School of Comprehensive Rehabilitation, Osaka Prefecture University, Habikino, Osaka, Japan

Hiroshi Shimizu

Hiroshi Shimizu Graduate School of Agriculture, Kyoto University, Kyoto, Japan

Young-Jun Son



Young-Jun Son The University of Arizona, Tucson, AZ, United States

Nobuhiro Sugimura

Nobuhiro Sugimura Osaka Prefecture University, Graduate School of Humanities and Sustainable System Science, Dept. of Sustainable System Science, Sakai, Japan

Masashi Sugano

Masashi Sugano School of Knowledge and Information Systems, Osaka Prefecture University, Sakai, Japan

Yusuke Tanigaki

Yusuke Tanigaki Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, Osaka, Japan

Nguyen Quang Thinh Osaka Prefecture University, Graduate School of Humanities and Sustainable System Science, Dept. of Sustainable System Science, Sakai, Japan

Russell Tronstad

Russell Tronstad The University of Arizona, Tucson, AZ, United States

R.F.M. van Elmpt

R.F.M. van Elmpt Horticulture LED Solutions, Signify, High Tech Campus 7, Eindhoven, The Netherlands

T. van den Bergh

T. van den Bergh Horticulture LED Solutions, Signify, High Tech Campus 7, Eindhoven, The Netherlands

Udo van Slooten

Udo van Slooten Philips Horticulture LED Solutions, Eindhoven, The Netherlands

Teruo Wada

Teruo Wada Graduate School of Life and Environmental Sciences, Osaka Prefecture University, Sakai, Japan

Yong Xu

Yong Xu Centre of Excellence for Research in Optoelectronic Agriculture, Fujian Agriculture and Forestry University, Fuzhou, China

Kazuhiko Yamamoto

Kazuhiko Yamamoto Tagajyo Factory, MIRAI Co., Ltd., Miyagi, Japan

Ryohei Yokoyama

Ryohei Yokoyama Department of Mechanical Engineering, Osaka Prefecture University, Sakai, Japan

Song Zheng

Song Zheng College of Electrical Engineering and Automation, Fuzhou University, Fuzhou, China

Introduction: Artificial Light-Type Plant Factories—Outline and a Vision for the Future

Masakazu Anpo, Hirokazu Fukuda, Teruo Wada
Osaka Prefecture University (OPU), Sakai, Japan

The world population has experienced continuous growth and, as a result, an increase in agricultural production with the use of fertilizers due to the success of ammonia synthesis from N_2 and H_2 using an Fe catalyst (including K or K_2O) supported on Al_2O_3, as reported by F. Haber and C. Bosch in the early 19th century. Since the beginning of mankind, we have been dependent on food bestowed by nature, i.e., grown under sunlight and natural photosynthesis, as shown in Fig. 1. However, such a marked increase in world population, rampant unregulated industrial growth as well as the overuse of ammonia-based fertilizers have all led to accelerated energy and food consumption, environmental pollution, pollution-related diseases, and abnormal climatic changes on a global scale. In addition, the earthquake-tsunami disaster of March 11, 2011, which destroyed the reactors of the nuclear power plants in Fukushima, Japan, has raised serious concerns not only over the supply of electric power, but also the pollution of farmlands and water sources by radioactive materials.

Under these current dire environmental conditions, food shortages and malnutrition are prevalent in many parts of the world. It can be said that the three basic needs of mankind are clothing, shelter, and food, and of these, clothing and shelter have been industrialized so that they can be provided with appropriate funding. However, food shortages arise from a variety of factors, both natural and manmade, which are often out of our control. Extreme climates, sudden natural disasters, the tendency for young people to work in areas other than agriculture leading to a lack of young farm workers, and regional conflicts or wars all lead to a slowdown or shutdown in food production.

Thus, one of the greatest challenges facing mankind will be to develop ecologically clean and safe, sustainable, and energy-efficient food production technologies, which will depend not only on the manpower of the younger generation, but can also be undertaken by senior and handicapped people in the community. To address these issues, the development of a

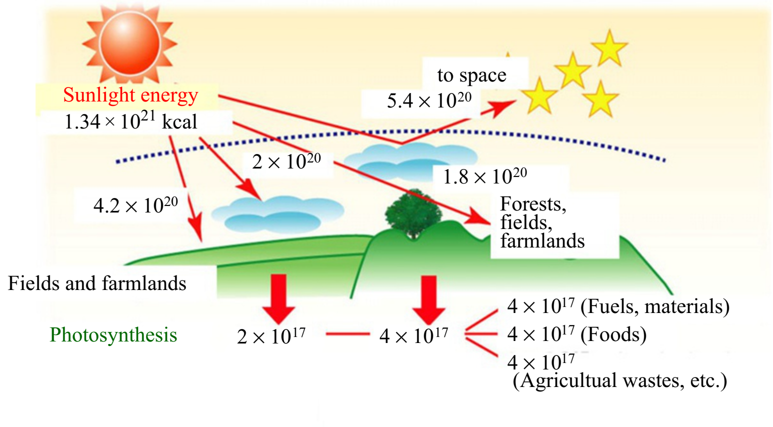


FIG. 1 Benefits from the Sun (photosynthesis).

plant factory which can produce vegetables without the damaging effects of any outside influences under artificial light such as LEDs powered by solar panels, i.e., the inexhaustible energy of the sun to supply electricity, will be a major step in achieving these objectives. Various advanced technologies are involved in the efficient operation of a functional plant factory such as optimal 24-h artificial lighting systems that take into account the circadian rhythm of plants, nutrient-rich hydroponics, low-cost air conditioning, various sensing technologies to create a homogeneous production environment in cultivation rooms as well as advanced automation and robotics technologies to save labor costs and maintain cleanliness in the production and harvesting areas.

What exactly is a plant factory? Plant factories are cultivation facilities that, through advanced and precise control of the production environment by monitoring the conditions and growth of plants, enable the year-round production of vegetables and other edible produce. Their development and widespread implementation is expected to allow a safe and stable supply of food, regardless of any adverse or disruptive natural or manmade influences such as global warming, climate change, pollution, conflicts, or any other potentially damaging circumstances. Thus, plant factories can provide much-needed relief and solutions to issues related to the environment, food supply, energy, and natural resources.

Plant factories are roughly classified into: (1) "fully artificial light-type," (2) "sunlight-type," and (3) "a mixed type" using both artificial and natural sunlight. In this book, we will focus on the development and future prospects of plant factories which use artificial light and a brief history of their development is shown in Fig. 2. The idea of a plant factory operating under artificial light had already been proposed by Christensen Farms, Ltd. in 1957, General Electric, Ltd. in 1970, and Kewpie Farms, Ltd. in 1990. However, such factories had not been economically viable until recent improvements in cost-efficient lighting technology.

Osaka Prefecture University (OPU) first established a plant factory using fluorescence lighting in 2011 as a training/education, observation, and demonstration-based facility (C21 building), being a fully artificial light-type plant factory with a class 10,000 level clean room in the campus of OPU. At the same time, the C20 building was also constructed next to

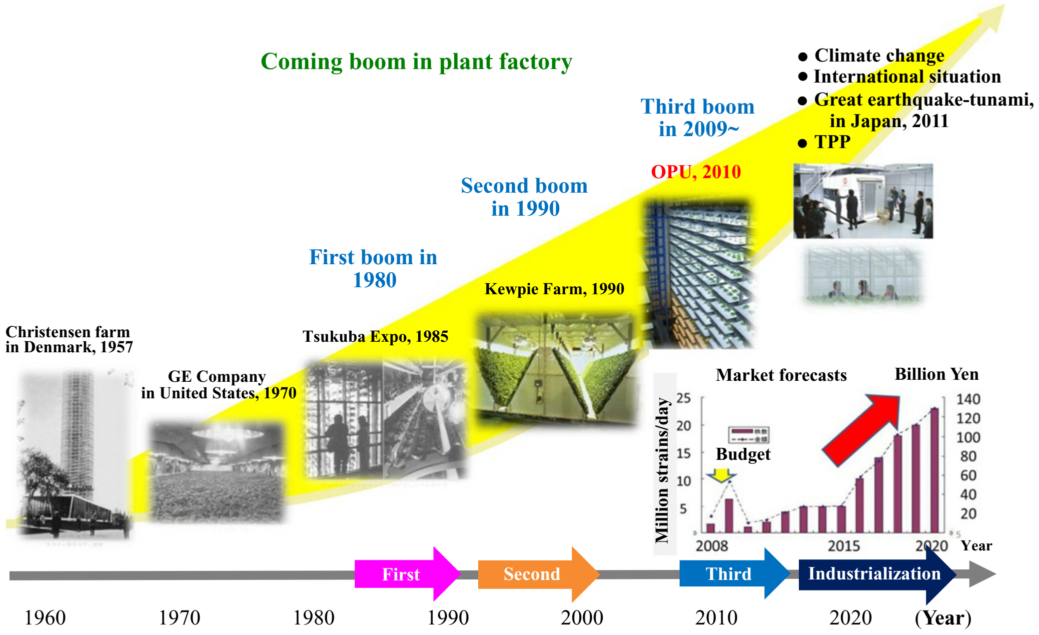


FIG. 2 Brief history of development of the artificial light-type plant factories.

C21 building. These facilities were the testing ground for various technologies in the low-cost, increased production of vegetables, reducing electric power consumption in collaboration with various companies for 4 years so that, in September 2014, another larger commercial-scale fully artificial light-type plant factory was established using LED lighting to produce 5000 lettuces a day in the same campus for various supermarkets and department stores.

Several important factors are involved in establishing such a large scale facility, as follows:

1. First, optimization of the solution culture using hydroponic cultivation is vital. The vegetables are cultivated in a clean room in a nutrient solution which includes optimum composition and concentration of chemical fertilizers for the plant growth which are supplied to the plants through absorbent polymer materials in an industrial-sized tray but do not use any soil, being able to avoid not only injury by continuous cropping (replant failure) but also poor or abnormal growth due to pathogens or insects which are common in outdoor or soil-based farm cultivation. The absorbent polymer material is shown in Fig. 3. As seen in Fig. 3, these absorbent polymer materials also play a role in supporting the plant. In hydroponic cultivation, the elements involved in vegetable growth can be completely controlled by optimizing the concentration of the chemical fertilizers dissolved in the water to meet various needs. For example, vegetables involving very low concentrations of potassium (K) can be produced for people with kidney disease since they cannot eat vegetables grown in outdoor fields due to the high concentration of the K element.
2. Air conditioning to create a clean and homogeneous production environment at low cost by reducing electric power consumption is also essential in the long-term operation of an

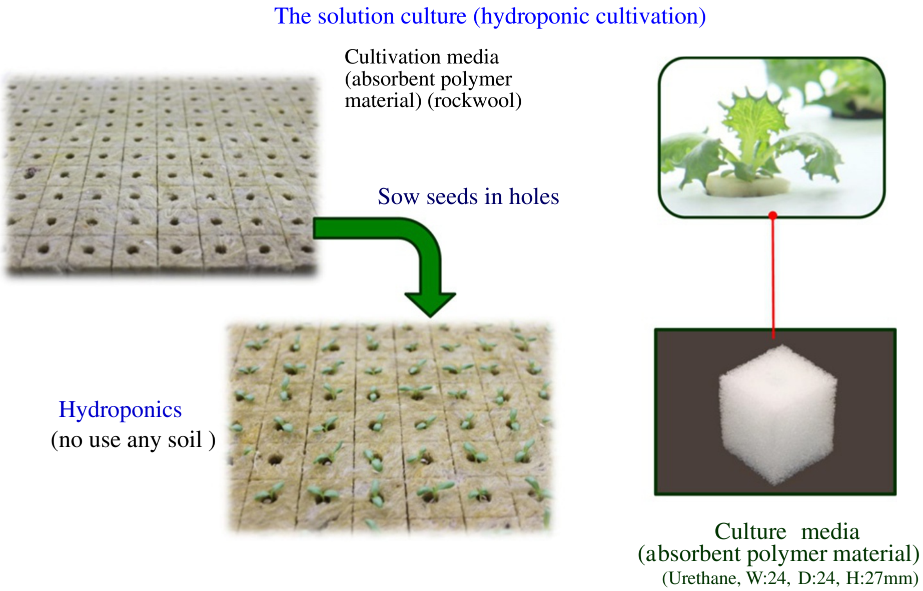
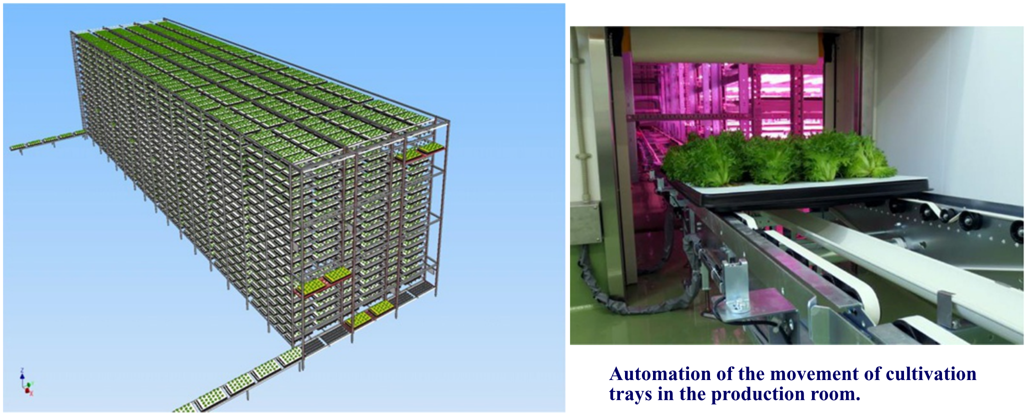

The solution culture (hydroponic cultivation)
Cultivation media (absorbent polymer material) (rockwool)
Sow seeds in holes
Hydroponics (no use any soil)
Culture media (absorbent polymer material) (Urethane, W:24, D:24, H:27mm)

FIG. 3 The solution culture (hydroponic cultivation) and its cultivation media.

artificially lighted plant factory. Control of the environment in the production clean room is carried out by sensors that monitor various factors such as vent hole positioning, wind direction and velocity, airflow, temperature, humidity, concentration of CO_2, light intensity as well as the content, concentration, and pH levels of the fertilizers and O_2 dissolved in water. In fact, it is designed to achieve the optimum temperature for the plant growth. It has also been found that the growth of vegetables is remarkably enhanced by an increase in CO_2 concentration in the plant factory which enhances photosynthesis, leading to the highly efficient production of vegetables within relatively short periods as compared to outdoor farming. Therefore, we set the concentration of CO_2 in the plant factories at about 3–4 times higher than in natural atmosphere.

3. The implementation and operation of low-cost lighting with a long lifetime is also an important factor so that LEDs were used. Thermal radiation should be low or the electricity expenses will be high due to high loading to the air conditioners. Short distance irradiation should be available for the efficient utilization of photons and, thus, stepped up production through tunable light sources and wavelengths. Only such careful monitoring and control of the intensity and wavelength of light will enable a highly functional, cost-efficient plant factory which can sustainably and constantly produce reasonably priced vegetables. Also, the installation, maintenance, and adaptability of the light sources should go smoothly and easily.

4. The overall operation and maintenance of a plant factory must also be efficient so that not only is the lighting completely artificial, but the transport systems are also fully automated, as shown in Fig. 4. Installation of a battery-operated, labor-saving automatic loading robot and the fully automated movement of the cultivation trays from the production room lines to the work area for harvesting have been implemented.



Automation of the movement of cultivation trays in the production room.

Installation of a large scale plant factory equipped with battery-operated automatic loading robot and the labor-saving fully-automated movement of cultivation trays from lines in production room to working area for harvesting.

FIG. 4 Fully automated transport systems in the plant factory.

5. The advantages of vegetables grown and nourished in an artificially lighted plant factory are thus many and varied. Harvesting, i.e., production, is very stable year-round, enabling the uninterrupted supply of vegetables at a constant price, no matter the weather. The vegetables are fresh, high in nutritional value, beautiful in color and texture, and most important, tasty. They are produced in a clean room under well-monitored conditions so that they are edible even without washing due to the very low number of bacteria and pathogens in comparison with soil-based vegetables. In addition, the safety and quality of vegetables are secured by the product tracking technology from the seedling diagnosis to cultivation and shipment.

As shown in Fig. 5, the further expansion of IT network systems will also facilitate more close agricultural and industrial collaborations that will connect the plant factories with research laboratories, scientists and supporting staff, IT companies as well as to the emerging markets for such factory-grown produce. Not only will such plant factories be beneficial to areas of the world where extreme climates or war may disrupt food growth and distribution, but can also contribute to societies where full automation can benefit aging communities with low birthrates and few young farm workers.

In this book, the scientists who have contributed to the development of the artificial light-type plant factories using LEDs have provided detailed discussions of their work. These include scientists from Taiwan, China, the United Kingdom, the Netherlands, Belgium, the United States, and Japan, covering the worldwide situation of plant factories to date. The publication of this book was first conceived in 2015 when the UN Climate Change Conference of Paris was held and the contents were updated in 2017. The promotion and widespread expansion of such large scale plant factories incorporating advanced technologies will be especially vital as resources become scarce and extreme climatic disruptions in our lives become more common.

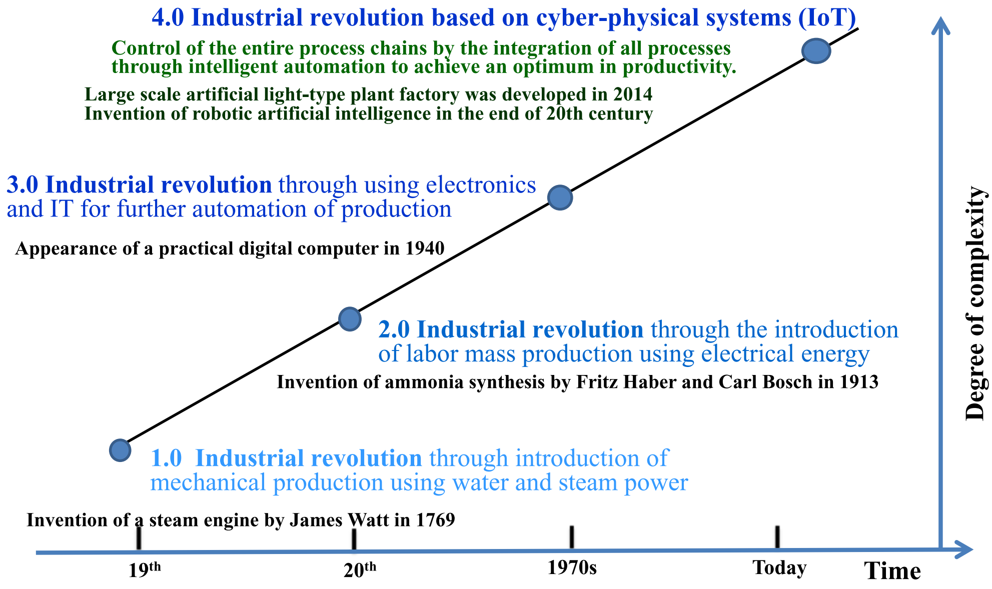

4.0 Industrial revolution based on cyber-physical systems (IoT)
Control of the entire process chains by the integration of all processes through intelligent automation to achieve an optimum in productivity.
Large scale artificial light-type plant factory was developed in 2014
Invention of robotic artificial intelligence in the end of 20th century
3.0 Industrial revolution through using electronics and IT for further automation of production
Appearance of a practical digital computer in 1940
2.0 Industrial revolution through the introduction of labor mass production using electrical energy
Invention of ammonia synthesis by Fritz Haber and Carl Bosch in 1913
1.0 Industrial revolution through introduction of mechanical production using water and steam power
Invention of a steam engine by James Watt in 1769
19th
20th
1970s
Today
Time
Degree of complexity

FIG. 5 The four steps of the industrial revolution in agriculture.

This book is meant for a wide audience including regular citizens, students, and academic, industrial, and government researchers in various disciplines related to such diverse fields as Mechanical, Light, Materials, and Sensing Engineering, Chemistry, Agriculture, Food Science, Life, Health & Environmental Sciences, and the various disciplines of Biology as well as Economics and Business as these areas are all involved in the development of the plant factory. We hope this book will contribute to solving the serious problems associated with worldwide food shortages such as disease, malnourishment, and famine by providing a means of clean and safe fresh food production for the 21st century and beyond, ensuring the survival of mankind for future generations.

PART I

EFFICIENT AND EFFECTIVE VEGETABLE CULTIVATION TECHNOLOGIES TO ENHANCE PRODUCTIVITY AND QUALITY

CHAPTER

1.1

Theory and Technology to Control the Nutrient Solution of Hydroponics

Teruo Wada

Graduate School of Life and Environmental Sciences, Osaka Prefecture University, Sakai, Japan

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1.1.1 INTRODUCTION

Hydroponics is the cultivation methods of plants without any soils. Water culture such as NFT or DFT and substrate culture using some media such as rockwool or coconut-coir are included in it. All plant factories use hydroponic systems, because of (a) automatic control of irrigation and fertilization, (b) saving labor, (c) keeping cultivation environment clean, (d) enabling to make cultivation beds multilayer, and so on. Sixteen minerals are needed to grow plant healthy. The minerals are called essential elements. Nine elements such as C, H, O, N, P, K, Ca, Mg, and S are called major elements, and seven elements such as Fe, Cu, Zn, Mn, Mo, B, and Cl are called minor elements. Thirteen elements in them excluding C, H,

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and O, which are supplied from water and CO_2, are needed to supply to plants as fertilizer. In soil culture, only N, P, and K, which are called three major elements, are supplied to plant as fertilizer generally, and most of any other elements are supplied from soil naturally. Because hydroponics does not use any soil, all 13 elements must be supplied to plants as fertilizer. The cultivation fluids which contain these 13 elements as optimum ratio and concentration for plant growth are the nutrient solutions. In hydroponics, water and fertilizer which are essential to plants' growth are supplied with nutrient solution. In this section, the basic theory and technique to control the concentration of major elements in the nutrient solution will be described.

1.1.2 NUTRIENT SOLUTION—CONTROL SYSTEM

The nutrient solution in hydroponic system is usually controlled by EC (Electric Conductivity), which is an indicator of concentration and pH. For example, EC of Enshi-shoho nutrient solution, which is Japanese standard nutrient solution, is about 2.4 $dS\,m^{-1}$, and EC for growing lettuce in the plant factory is usually controlled 1.2–1.6 $dS\,m^{-1}$. So, almost half strength of Enshi-shoho is used for lettuce growth. pH is adjusted to around 6.0. pH should not be over 7.0 because this situation causes precipitation of Ion and Manganese. Basic system for controlling the nutrient solution in closed hydroponic system is described in Fig. 1.1.1.

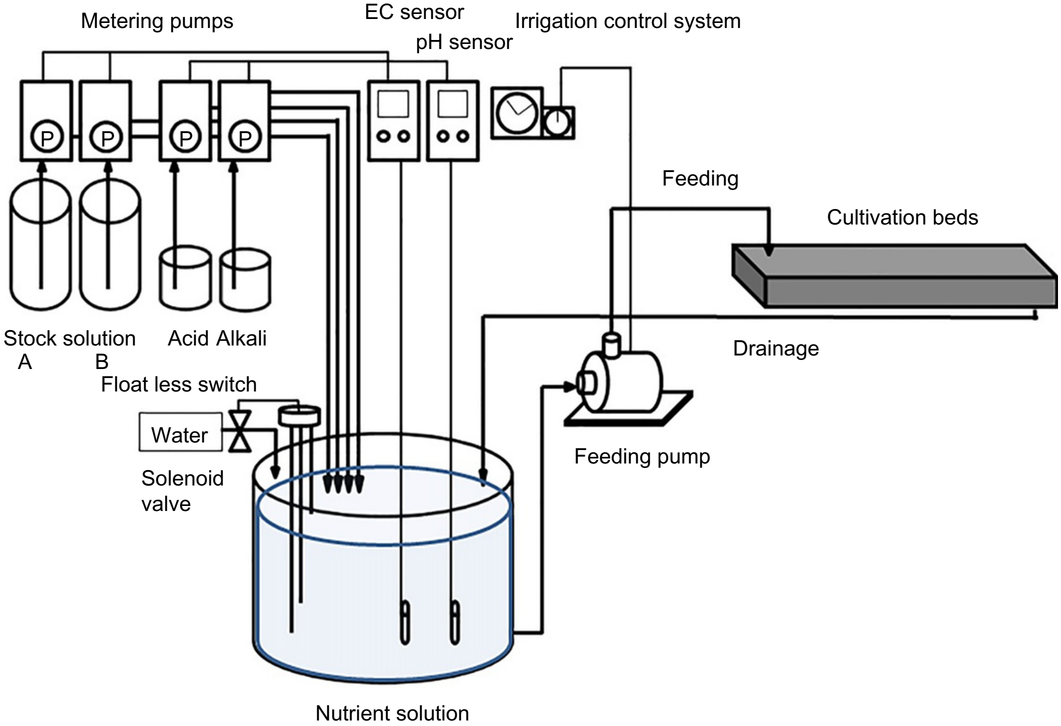


FIG. 1.1.1 Basic system for controlling the nutrient solution in closed hydroponics.

It consists of a solution tank, two kinds of stock solution (basically, calcium nitrate and others), acid and alkali (generally, 5 N phosphate and 5 N potassium hydroxide), level sensor, EC sensor, pH sensor, metering pumps for injecting every solution to the nutrient solution, irrigation system, and so on. A kind of disinfection system such as UV or ozone is also installed in a certain system. Basic procedure is below: (1) water level become low by plants' absorption of water, (2) water is supplied to solution tank, (3) stock solutions are supplied until the EC become set value, (4) acid or alkali was added to the nutrient solution if it is needed. Analysis of concentrations of mineral elements in the nutrient solution is carried out periodically, but automatic control of the concentration of each mineral elements is not realized. So, adjusting the formula of the additional nutrient solution is carried out manually.

1.1.3 CALCULATING NUTRIENT UPTAKE BY PLANTS

1.1.3.1 Principle of Yamazaki Formula in the Nutrient Solutions

Yamazaki formula is one of famous nutrient solution in Japan. The formula has many kinds of compositions which are suitable for growing each vegetable. Dr. Yamazaki measured the apparent concentrations of nutrient uptake by plants. The concentrations were measured by following procedure as shown in Fig. 1.1.2. Plants are grown in the bucket by aerated water culture until the volume of the nutrient solution become 70%–80% of start volume. Let a volume of the nutrient solution and a concentration of each element at the start of cultivation be w_1 and n_1, and a volume of the nutrient solution and a concentration of each element at the end of cultivation be w_2 and n_2, respectively. Apparent concentration of the nutrient uptake by plants (N/W) can be calculated as below:

$$\frac{N}{W} = \frac{n_1 \times w_1 - n_2 \times w_2}{w_1 - w_2} \tag{1.1.1}$$

This is the principle of Yamazaki formula. Dr. Yamazaki thought that each plant has its own property of nutrient uptake. N/W of every major element was calculated under various conditions (e.g., some level of EC or pH, different plant ages, different season, and so on) and optimum compositions of nutrient uptake by many kinds of plant were published as

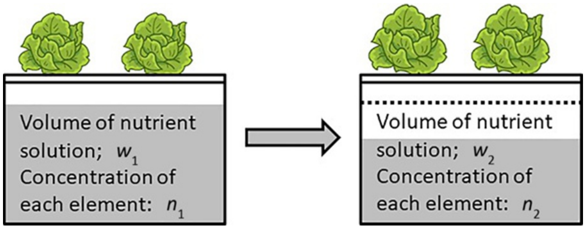

Volume of nutrient solution; w_1
Concentration of each element: n_1
Volume of nutrient solution; w_2
Concentration of each element: n_2

FIG. 1.1.2 Principle of Yamazaki formula.

Yamazaki formula [1]. It is thought that the concentration of every element in the nutrient solution would not change much and stable growth could be realized in closed hydroponic system if the concentrations of every element in the nutrient solution and nutrient uptake by plants are equal.

1.1.3.2 Application of Yamazaki's Method to Closed Hydroponic System

Yamazaki's method can be applied to closed hydroponic system described in Fig. 1.1.1. Different points between Yamazaki's method and closed hydroponic system are below: (a) volume of the nutrient solution is constant, (b) additional nutrient solution is supplied additionally, (c) amount of water absorbed by plants is equal to the amount of nutrient solution additionally supplied, which is unknown because the concentration is controlled by EC.

Firstly, dilution ratio of stock solution ($d=(n \cdot wsc+wsw)/wsc$) has to be calculated from the values of the number of tanks of stock solution, consumption of each stock solution (wsc), and the volume of supplied water (wsw). And then, concentration of each element added from the stock solution in supplied nutrient solution has to be calculated. It can be calculated by nsc/d when the concentration of each element in the stock solution is nsc. When you make stock solution as 100 times concentrated solution and the concentration in nutrient formula is nss, nsc is 100 nss. For example, concentration of NO_3^- in the stock solution is 1600 mmol L^{-1} when you make 100 times concentrated solution and concentration of NO_3^- in the nutrient formula is 16 mmol L^{-1}. And then, concentration of each element in the water supplied (nsw) is added to calculation. That is, concentrations of each element in the supplied nutrient solution can be calculated with $ns=nsc/d+nsw$, where the same water is used to make stock solutions. Secondary, calculation as below is done. Let the total volume of the nutrient solution including the solution in the tank, solution circuit, and cultivation beds be w_0, concentrations of each element at the start and the end of measurement be n_1 and n_2, the volume of supplied nutrient solution be $ws=n \cdot wsc+wsw$, and the concentration of each element in supplied nutrient solution be $ns=nsc/d+nsw$, respectively. Apparent concentration of the nutrient uptake by plants (N/W) can be calculated as below:

$$\frac{N}{W}=\frac{n_1 \times w_0+ns \times ws-n_2 \times w_0}{ws} \tag{1.1.2}$$

where

$ns=\frac{nsc}{d}+nsw, \quad d=\frac{n \cdot wsc+wsw}{wsc},$
$ws=n \cdot wsc+wsw$

An example of calculation of apparent nutrient uptake by plants is shown in Table 1.1.1. Enshi-shoho nutrient solution is used. The number of tanks of stock solution is 2. Concentration ratio of each stock solution is 100 ×. Concentration of each element in Enshi-shoho standard nutrient solution (nss), in the water (nsw), and in the nutrient solution at the start (n_1) and end (n_2) of measurement are shown in Table 1.1.1. Total volume of the nutrient solution (w_0) is 5000 L. The volume of supplied water (wsw) and consumption of each stock solution (wsc) are 19,800 and 100 L, respectively. So, $d=200$, $ws=20{,}000$ L, and $nsc=100$ nss.

TABLE 1.1.1 Example of Calculation of Apparent Nutrient Uptake by Plants

	NO_3-N	H_2PO_4-P	K	Ca	Mg
Enshi-shoho (*nss*)	16	1.3	8	4	2
$nsc = 100\,nss$	160	130	800	400	200
Water (*nsw*)	0.2	0	1.2	0.9	0.15
n_1	8.0	1.3	6.0	1.0	1.0
n_2	9.0	0.3	4.0	1.5	3.0
n_s	8.2	0.7	5.2	2.9	1.2
N/W	8.0	0.9	5.7	2.8	0.7

mmol L^{-1}.
$w_0 = 5000$ L; $wsw = 19{,}800$ L; $wsc = 100$ L.
Concentration ratio of stock solution is 100.
The number of tanks of stock solution is 2.

1.1.4 MANAGEMENT OF NUTRIENT CONCENTRATION

In case of lettuce, nutrient compositions of standard nutrient solutions which are usually used in plant factory and Yamazaki lettuce which is made from the nutrient uptake by lettuce are shown in Table 1.1.2. The composition of Yamazaki lettuce is not an original composition, but recalculated as EC to be 1.2 dS m^{-1}. These values indicate that the composition of standard nutrient solution and Yamazaki lettuce is different, especially in K and Ca. It is easy to imagine that nutrient composition would become abnormal if standard nutrient solution is used for lettuce growth in closed hydroponic system. Actually, deficiency of K and accumulation of Ca often occur in growing lettuce in a plant factory. Furthermore, nutrient uptake of plants changes variously depending on cultivar, growing environments, concentration of the nutrient solution, and so on. So, periodical analysis of nutrient composition and adjusting formula of added nutrient solution are important.

The nutrient composition would be stable if the concentration of each element in the nutrient solution and in plant uptake is equal. However, in plant factory, different compositions of nutrient solution to plant uptake are often used because of the following reasons. Nutrient

TABLE 1.1.2 Composition of Standard Nutrient Solutions and Yamazaki Lettuce

	NO_3-N	NH_4-N	H_2PO_4-P	K	Ca	Mg
Half strength of Enshi-shoho	8.0	0.7	0.7	4.0	2.0	1.0
Half strength of OAT Agrio A	8.3	0.8	0.9	4.3	2.1	0.8
Yamazaki lettuce	8.5	0.7	0.7	5.6	1.4	0.7

mmol L^{-1}.
Yamazaki lettuce is recalculated as EC is 1.2 dS m^{-1}.

FIG. 1.1.3 Example of the nutrient composition for the best growth and nutrient uptake by a certain plant.

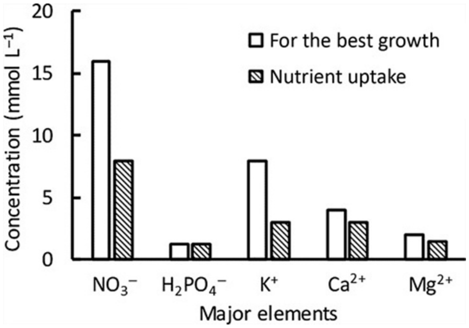
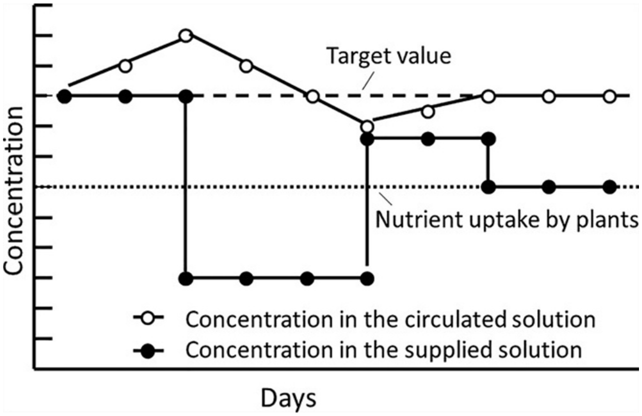


FIG. 1.1.4 Model of controlling the nutrient concentration in the nutrient solution.



composition for the best plant growth and nutrient uptake by plants are different. An example of nutrient composition for the best plant growth and nutrient uptake by plants in a certain plant is shown in Fig. 1.1.3. The data indicates that the best plant growth could not be achieved if the nutrient solution according to the nutrient uptake is used. The nutrient solution including high Ca and low K is often used in order to decrease the incidence of tip-burn, which is one of physiological disorders in lettuce plants. Or, sometimes, the nutrient solution including low nitrate is used in order to decrease nitrate content in leaves. That is, target value of the nutrient composition and nutrient composition of plant uptake are different. So, in order to make the nutrient composition in the nutrient solution the target value, nutrient composition in the supplied nutrient solution must be adjusted. Though decision of target value is difficult, some examples are published [2, 3]. The adjusting is carried out usually as below: the concentration of an ion in the supplied solution is decreased when concentration of the ion in the circulated solution becomes higher than target value, and the concentration of an ion in the supplied solution is increased when the concentration of the ion in the circulated solution becomes lower than the target value as shown in Fig. 1.1.4.

1.1.5 CALCULATION METHOD FOR ADJUSTING THE NUTRIENT COMPOSITION

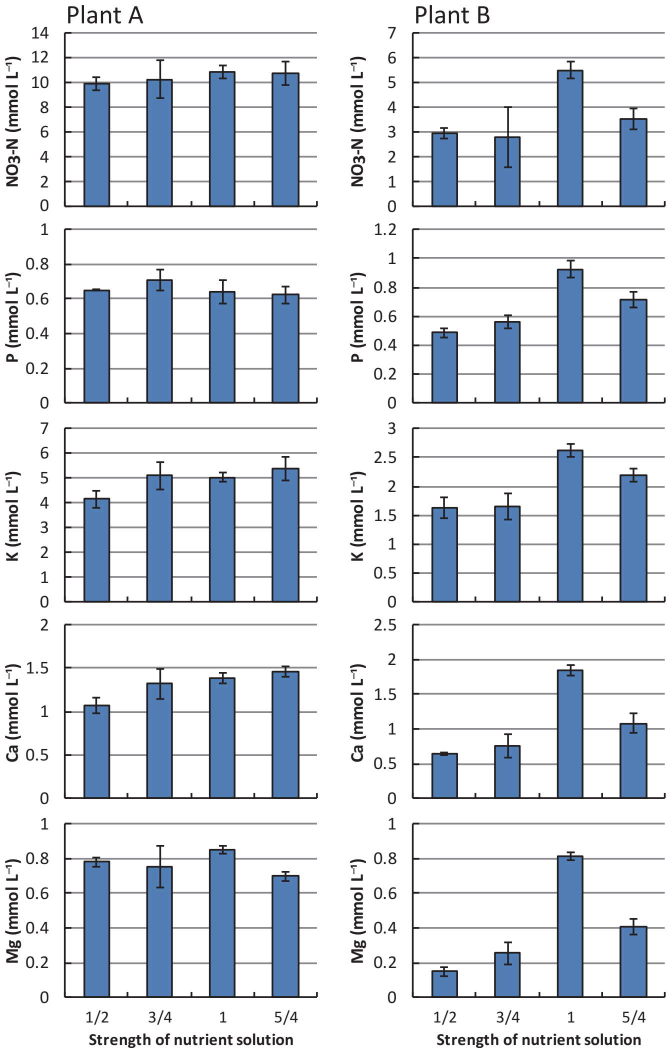
The nutrient composition in supplied nutrient solution can be calculated using Eq. (1.1.2). It is assumed that the measurement of apparent nutrient uptake was carried out for a certain period (measurement period), and you want to adjust the nutrient composition in the nutrient solution to near a target value for the next same period (adjustment period). Put the present value of the concentration of each element to n_1, and put the target value to n_2. N/W has been measured in measurement period. It is assumed that w_0 and ws are the same value between measurement period and adjustment period. The value of ns could be gotten from Eq. (1.1.2). Here, total equivalent of ions between n_1 and n_2 must be the same value because EC is same. So, mmol L^{-1} has to be changed to meq L^{-1}. The calculation of the change is carried out as below: NO_3^- mmol L^{-1} is 1 me L^{-1}; $H_2PO_4^-$ mmol L^{-1} is 1 me L^{-1}; K^+ mmol L^{-1} is 1 me L^{-1}; Ca^{2+} 1 mmol L^{-1} is 2 me L^{-1}; Mg^{2+} 1 mmol L^{-1} is 2 me L^{-1}; NH_4^+ 1 mmol L^{-1} is 1 me L^{-1}; SO_4^{2-} 1 mmol L^{-1} is 2 me L^{-1}. That is, it can be calculated by multiplying the molar concentration by the electric charge of ions. Wada et al. actually applied this method to the nutrient solution for lettuces in a plant factory [4].

The adjustment would not necessarily go well, even if you use Eq. (1.1.2). When adjusting, it is necessary to pay attention to the following points. (a) The apparent nutrient uptake of plants changes depending on plant age or growth environments. (b) The nutrient uptake is different with ions. The uptake of NO_3^- would not change so much. But the uptake of $H_2PO_4^-$ or K^+ might increase when their concentration in the nutrient solution is higher. Reversely, the uptake of Ca^{2+} and Mg^{2+} might decrease when their concentration in the nutrient solution is higher. An example is shown in Fig. 1.1.5 [5]. In case of plant A, the nutrient uptake is almost constant regardless of nutrient concentration. While, in case of plant B, the nutrient uptake tends to change with nutrient concentration. It is thought that adjustment of nutrient composition is more difficult in plant B. (c) The effects of ions to plant must be considered. NO_3^- effects to plant growth strongly, but $H_2PO_4^-$, K^+, or SO_4^{2-} have little effect on plant growth even if their concentration is higher. The concentration of NH_4^+ affects pH so much and could cause the incidence of tip-burn in lettuces or blossom-end rot in tomatoes. (d) The balance of anion and cation must be considered. For example, when you want to change the K^+ concentration, you cannot change only K^+ concentration, but the concentration of accompanying ion also changes. You have to consider what fertilizer you use, e.g., KH_2PO_4, KNO_3, or KCl.

1.1.6 ADJUSTMENT OF PH

Optimum pH of the nutrient solution is 6.0. The pH higher than 7.0 will cause precipitation of Fe or Mn. The pH lower than 4.5 will cause root injury. In general, pH of closed hydroponics initially goes down and then goes up. This depends on concentration of NH_4 ion. When pH of nutrient solution is higher, it is desirable to check the concentration of bicarbonate in water. It can be measured by bicarbonate method using pH meter or EC method using EC meter. In both methods, 1/100 N sulfuric acid is titrated for measurements [6]. When the concentration

FIG. 1.1.5 Effect of the strength of nutrient solution on the apparent nutrient uptake by plants. Enshi-shoho nutrient solution was used.



of bicarbonate is over 50 ppm, it is necessary to neutralize with nitrate or phosphate before making the nutrient solution.

It is thought that pH would be lower when plants absorb more cations, and it would be higher when plants absorb more anions. For example, when Ca or Mg concentration in the nutrient solution is higher, K absorption by plants could be suppressed and pH would be higher. If you use nitrate or phosphate to adjust pH in such a case, plant absorption of such ions might be increased and make it difficult to decrease pH. So, ion balance in the nutrient solution must be considered firstly to adjust the pH.

There are three methods, that is, EC, ammonium ion concentration, and acid or alkali as shown in Table 1.1.3 [7]. When pH is higher and you want to adjust pH lower, you have

TABLE 1.1.3 Methods to Adjust pH

Change of pH	Higher	Lower
Cause	Plant absorption of anions such as NO_3^-, $H_2PO_4^-$ is active, or the ions such as Ca^{2+}, Mg^{2+} are accumulated in the nutrient solution	Plant absorption of cations such as NH_4^+, K^+ is active, or the ions such as SO_4^{2-}, $H_2PO_4^-$ are accumulated in the nutrient solution
Adjusting method	Adjusting pH lower	Adjusting pH higher
EC	Set higher	Set lower
Concentration for NH_4^+	Higher concentration	Lower concentration
Acid or alkali	Addition of acid	Addition of alkali

to set EC higher or increase NH_4^+ concentration or add acid. When pH is lower and you want to adjust pH higher, you have to set EC lower or decrease NH_4^+ concentration or add alkali. Generally, nitrate or phosphate is used as acid, and potassium hydroxide is used as alkali. Used concentration of either acid and alkali is about 5 N. EC affects plant growth, ammonium ion concentration affects the incidence of tip-burn or blossom-end rot, and much addition of acid or alkali disturbs the ion balance in the nutrient solution. It is important to use the three methods in a balanced manner.

1.1.7 CONCLUSIONS AND PROSPECTS

As described above, the nutrient composition for a plant growth and the composition of nutrient uptake by the plant are different. Firstly, it is important to find the best nutrient composition which gives the best plant growth without any physiological disorders. After that, the nutrient composition in the nutrient solution can be kept at the best value by measuring the nutrient uptake by plants based on analyzing the nutrient solution. In the future, the ion sensors to measure every ion in the nutrient solution may be developed. Then, the nutrient solution will be fully controlled automatically. Though some sensors have already been used, the sensors are not enough to measure all elements and not necessarily cheap and durable in order to use them in the commercial plant factories. Therefore, the grower has to have technique and skill to control the nutrient solution properly. We wish that this chapter would be useful for every grower to control the nutrient solution by not only EC and pH, but also its nutrient composition.

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CHAPTER

1.2

Cultivation Technology for Vegetable and Herb Production

Hajime Furukawa

Graduate School of Life and Enviromental Science, Osaka prefecture University, Sakai, Japan

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1.2.1 INTRODUCTION

Functional vegetables consist of the following: (1) a high content of specific ingredients (e.g., green pepper: ascorbic acid), (2) increased content of specific ingredients by breeding (e.g., carrot: β-carotene), (3) low specific content that may harm the human body, (4) specific ingredient content controlled using plant factory.

On the other hand, herbs are useful plants that have scents, flavors, bitterness, etc. [1], including those that are used only for fragrance, such as potpourri instead of food, and those

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that are used as tea like rose hips. As described above, herbs are not consumed in large quantities as food materials, but are consumed in small amounts and are useful plants expected to exhibit strong characteristics (scent, flavor, bitterness) [2]. In addition, some herbs contain many functional ingredients such as β-carotene (e.g., basil: Vitamin A) and ascorbic acid (e.g., rucola: Vitamin C), which are also expected as a source of these [3]. Many harps have been cultivated in a cool weather, so the ordinary cultivation method in Japan, there is a problem that quality and yield of scent, flavor, bitterness and the like are lowered due to the transition to the season and the reproductive growth phase [4,5]. Plant factory with artificial lighting controls environment such as light, temperature, and the humidity at a high level; anniversary supply is possible with quality and the yield that are high with the coolness-related use of plant such as the herb stably. In this report, I explain a cultivation technology about the functionality vegetables in plant factory with artificial lighting and production of the herb from the data which I obtained by the herb production proof project in the University of Osaka Prefecture plant factory research center [6] in detail and examine a current problem and the prospects for the future.

1.2.2 CULTIVATION TECHNIQUE

1.2.2.1 Raising Seedling

Fig. 1.2.1 shows the number of the germinated seeds, (germination rate) the basil, coriander, Italian parsley, cerfeuil, fifth day after sowing. Basil and cerfeuil had high germination rate more than 70%, but that of coriander, Italian parsley, and spearmint was extremely low with 10%. In this way, the germination rate is low in some herbs, unlike vegetables such as leaf lettuce and tomato; breeding has not progressed much in herbs. On the other hand, the germination rate of the leaf lettuce, which is the main vegetable in the fully artificial light type plant, is about 98%, and the germination rate of tomato which is the main vegetable in the solar light use type plant is also high as 90%. Also, compared to herbs, there is little variation in growth in leaf lettuce or tomato. In this way, the germination rate is high in tomatoes and leaf lettuce, and it is the characteristic brought about by breeding that the growth is consistent.

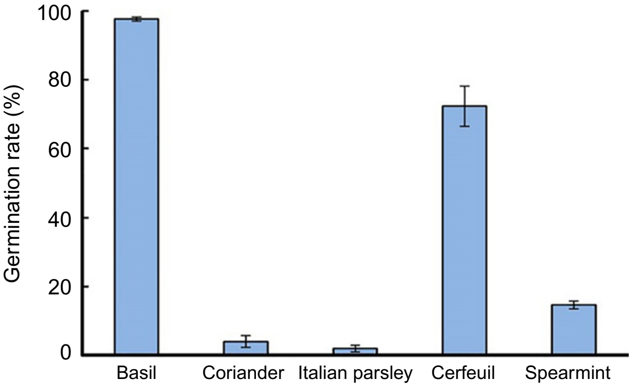

FIG. 1.2.1 Germination rate of some herb. Values are means ±SE ($n=3$).

Therefore, when choosing herbs as a work, it is necessary to investigate the germination rate and the maturity of growth in advance and prepare necessary number and seedling number from this result.

In spearmint, peppermint, watercress, and other herbs, it is easy to propagate cuttings, so seedling production by vegetative propagation as well as seed propagation is also possible.

1.2.2.2 Cultivation

In the herb proof demonstration project, basil, cerfeuil, peppermint, and spearmint were tested from the result of preliminary experiment by hydroponic cultivation in the glass room. For the nutrient solution, EC was measured at the appropriate time by EC meter using Otsuka A prescription, and the concentration of nutrient solution was kept constant by adding Otsuka A prescription nutrient solution. The light conditions were daylight length 16h, light intensity 200 μmol × m^{-2} × s^{-1}. The cultivation panels used were 600 mm × 900 mm 24 holes (24 strains per panel). The four herbs tested under this cultivation condition showed normal growth. In order to reduce the utility cost, even if the light intensity was 140 μmol × m^{-2} × s^{-1}, the yield and quality of these four herbs did not change. This is because many herbs originate from Europe and so on, so that strong light intensity is not required. It is possible to think that herbs are suitable crops for plant factories because it is possible to cultivate water with the same light intensity and culture solution as the leaf lettuce which is a typical vegetable produced in plant factories.

1.2.2.3 Harvest

The shipping form of herbs is not shipped for each stock like leaf lettuce, but is a shoot or leaf, so it is shipped out by cutting off a part of the above ground part. For this reason, it is possible to continue the production, harvesting, and shipping cycles of cultivating herbs after harvest and cutting out and harvesting and shipping them when the sites of use grow. Such production, harvesting, and shipping cycles can be repeated for about 1 year. It is an advantage of a fully artificial light type plant factory that it is possible to carry out such an anniversary like this cycle. In long-term cultivation for more than 1 year, the occurrence of pests is more likely to occur, and the quality of the product because of a decrease in growth rate due to aging and curing of the harvest portion is deteriorated.

1.2.3 EXPECTED FUNCTIONALITY OF VEGETABLES AND HERBS

1.2.3.1 Definition of Functionality

According to the definition of functional foods, the functionality consists of a primary function (nutritional function), a secondary function (sensory function), and a tertiary function (physical condition adjustment function) [7]. The primary function is the function of supplying nutrients and calories which are the minimum necessary for living. The secondary function is related to the sense of taste and scent, and it is a function to make it feel delicious. The tertiary function is a function such as defense of the body, prevention of diseases, recovery of diseases, adjustment of physical rhythm, and aging suppression· It is a function that consumers are most interested at present. What is expected of vegetables are primarily primary and secondary functions, and what is expected of herbs is mainly secondary and tertiary functions. As for vitamins contained in the primary function, desires to expect antioxidant actions of vitamin A and vitamin C both in vegetables and herbs have been high in recent years [8].

1.2.3.2 Nitrate Ion

Baby's breath (*Gypsophila paniculate* L.) releases an unpleasant odor called isovaleric acid. Therefore, attempts have been made to increase the commercial value by reducing the amount of isovaleric acid released [9]. In this way, reducing the content of components that cause harm or discomfort to the human body is also included in the category of functionality in a broad sense. Persons in need of artificial dialysis are expected to have low potassium ion intake. Low potassium content lettuce production by plant factory is such a good example. In vegetables and herbs, the best known objectionable substance is nitrate ion. Whether it is soil or hydroponic, if nitrate nitrogen is applied as a fertilizer, nitrate ions accumulate in the plant body [10]. Since nitrate ions are converted into substances harmful to the human body when accumulated at high concentrations in plants; the content in vegetables is strictly regulated in Europe [11]. For example, the nitrate ion content of lettuce which is not planted in facility cultivation from autumn to winter is $450\,\mathrm{mg} \times 100\,\mathrm{g}^{-1}$, the summer content from autumn is within $350\,\mathrm{mg} \times 100\,\mathrm{g}^{-1}$. In addition, the content of spinach from autumn to winter is $300\,\mathrm{mg} \times 100\,\mathrm{g}^{-1}$, from summer to autumn is $250\,\mathrm{mg} \times 100\,\mathrm{g}^{-1}$. The results of measurement of nitrate ion content for basil and cerfeuil cultivated at the commercial and plant factory research center are shown in Fig. 1.2.2. The average nitrate ion content of basil and cerfeuil was lower than the EU regulation value, the same value as that of commercial products in basil, and statistically significantly lower in cerfeuil. In this way, nitrate ion can be reduced in basil and cerfeuil due to the nitrogen management of the culture liquid in the plant factory. In addition, nitrate ion can be reduced by selecting the shipping site. Plant petiole plays a role of temporarily storing nitrate ions. Therefore, in vegetables and herbs such as leaf lettuce, ice plants, mitsuba, coriander, cerfeuil, and Italian parsley, the nitrate ion content of the petiole is more than twice as high as that of the leaf (data not shown). Therefore, by decreasing the amount of petiole in the shipment, it is possible to reduce the nitrate ion content as a commercial product.

1.2.3.3 Number of Viable Microorganisms on Plant Surface

Cut vegetables packed in plastic bags can be eaten raw without washing. This is because it is cleaned after the sterilization process. Being able to use vegetables and herbs without washing can usually differentiate from cultivated vegetables. This adds value added to cut vegetables. This is because cleaning is necessary because about 10^5–10^8 microorganisms per 1 g are adhering to the surface of vegetables and herbs usually cultivated. Many of these microorganisms are human resident bacteria adhering from humans in the process of cultivation, harvesting, shipping, distribution, and product adjustment [12]. In vegetables and herbs produced at a plant factory, it is usually differentiated from cultivated vegetables in that it is not

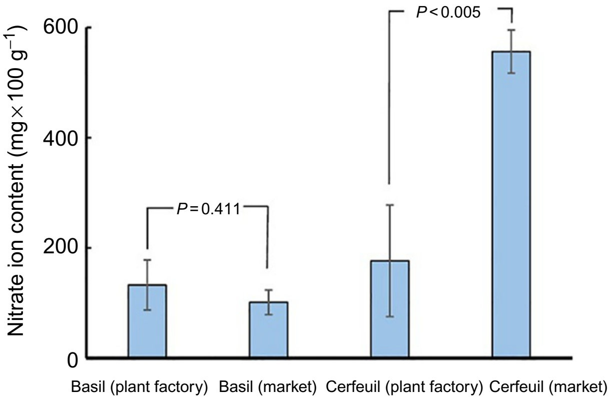

FIG. 1.2.2 Nitrate ion content of basil and cerfeuil. Values are means ±SE ($n=3$). The statistical difference was determined by Student's *T* test.

necessary to wash, from which it can be inferred that this will add value as a product. For this reason, plants produced in a plant factory are desired to have few CFU (colony forming units) in viable bacterial examination, which is an indicator of hygiene control. Actually conducting a live bacteria test, the CFU of commercially available verbs is 10^5–10^7, whereas the CFU of herbs produced at the plant factory research center was about 10^3. At our plant factory research center, gloves, masks, and dustproof clothing to wear and hand washing before work are required, and such hygiene management contributes to the reduction of CFU. From cultivation of *Arabidopsis thaliana* in the plant growth device artificial to cultivation of hydroponics of tomatoes in facility horticulture, it is possible to admit small fly like *Drosophila*. Many of these are a kind of flies belonging to the family *Sciaridae*. Since this fly uses cyanobacteria (photosynthetic bacteria) and nutrient-derived dead plants, which are nutritious culture fluids for nutrient cultivation, they may also be found in plant factories where sanitation control is bad. *Sciaridae* never harms leaf vegetables and fruit vegetables, but since it acts as a vector of microorganisms, there are cases where CFU showed 10^7 when it propagated in a plant factory. Thus, in a fully artificial light plant factory, it is desirable to install air curtains at entrances and exits from hygiene control as well as measures against pest and insect damage, to prevent invasion of small animals such as *Sciaridae*. Cyanobacteria adhere to cultivation equipment and harvested materials in plant factories, hygienically deteriorating the appearance as a product, and when hygiene control is not good, they may be observed as colonies by viable bacterial tests. Countermeasures against cyanobacteria are only to mask the nutrient solution and inhibit the photosynthesis of cyanobacteria and suppress propagation.

Thus, in a fully artificial light type plant factory, a management system to prevent the ingress and propagation of organisms is required.

1.2.3.4 Functional Ingredients of Plants

Carotenoids (β-carotene, lycopene, β-cryptoxanthin, and the like) and polyphenols (such as anthocyanin) can be mentioned as functional ingredients that can be expected to increase the content of vegetables and herbs produced at plant factory. Both carotenoids and polyphenols have antioxidant activity. Since ascorbic acid that acts as vitamin C is not recognized as a

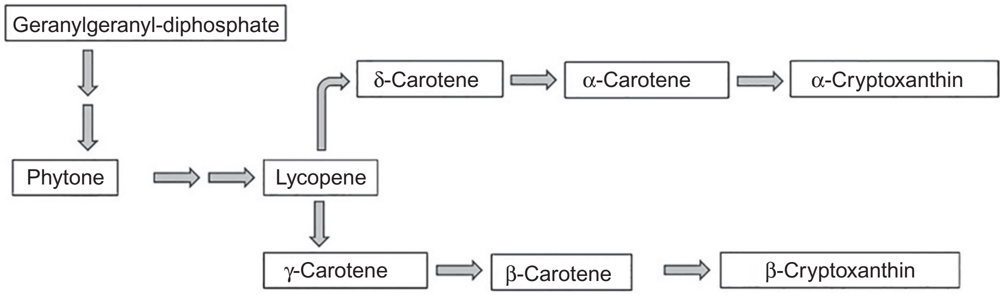

FIG. 1.2.3 Metabolic pathway of carotenoids.

vitamin, but rather as a functional ingredient having antioxidant activity, it will be explained as a functional ingredient in this article as well. Fig. 1.2.3 shows part of the plant's carotenoid synthesis pathway. All of α-carotene β-carotene, lycopene, and β-cryptoxanthin have antioxidant activity. β-carotene is a carotenoid abundantly contained in leaf lettuce and acts to react with active oxygen produced in plants by photosynthesis and ultraviolet rays to suppress its oxidation. Fig. 1.2.4 shows a part of plant anthocyanin synthesis pathway. Anthocyanin is a red pigment contained in sunny lettuce or strawberry, it is a glycoside in which anthocyanidin (pelargonidin, cyanidin, delphinidin, etc.) is bonded with a sugar or a sugar chain and absorbs sunlight ultraviolet rays. It has a function of inhibiting the formation of active oxygen. We have confirmed the phenomenon that the synthesis of anthocyanin is suppressed when the blue light is little by LED illumination on sunny lettuce cultivated in hydroponics. Fig. 1.2.5 shows the active oxygen scavenging system of plants. As plants produce active oxygen by ultraviolet irradiation or photosynthesis, they have an active oxygen scavenging system as a system for erasing these active oxygen. As can be seen from the metabolism of active oxygen scavenging system, ascorbic acid production is necessary for erasing active oxygen. From the viewpoint of plant physiology, carotenoids, polyphenols, and ascorbic acid are induced in plants by giving conditions such as generating active oxygen. The total polyphenol content of basil produced at the plant factory research center was $117 \pm 12\,\mathrm{mg} \times 100\,\mathrm{g}^{-1}$ (±SE), which was larger than that of anthocyanin rich grape

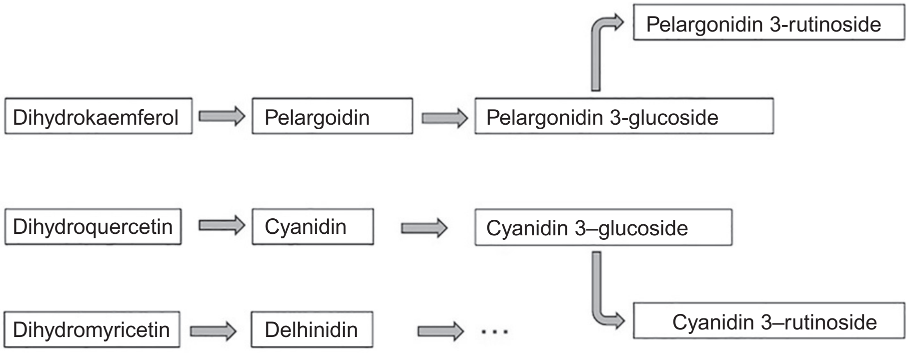

FIG. 1.2.4 Metabolic pathway of Anthocyanin.

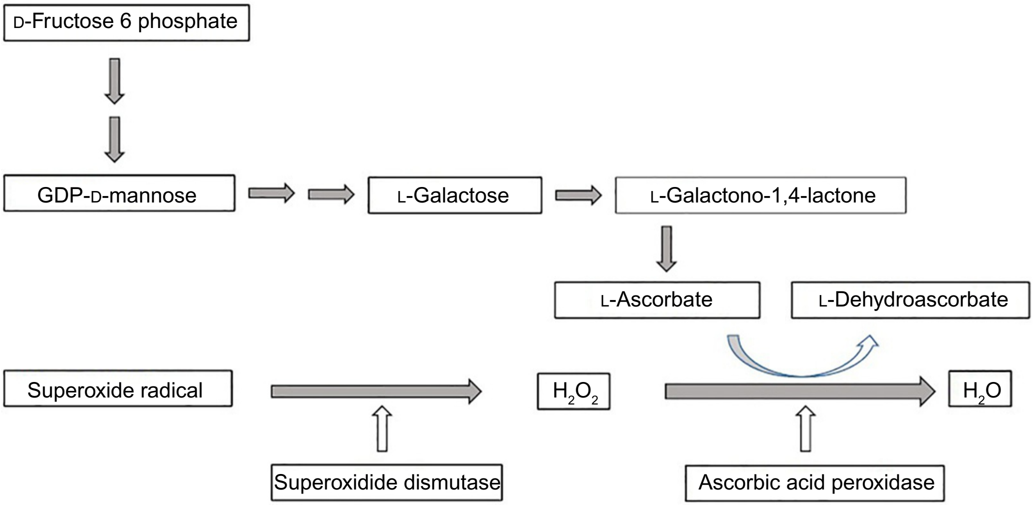

FIG. 1.2.5 Active oxygen scavenging system.

"Kyoho." And the total polyphenol content of the leaf lettuce produced at the center was $117 \pm 12\,\text{mg} \times 100\,\text{g}^{-1}$, which was comparable to that of mizuna rich in anthocyanin. Similarly, the ascorbic acid content of basil and cerfeuil produced at the plant factory research center is $54 \pm 11.5\,\text{mg} \times 100\,\text{g}^{-1}$ and $44 \pm 11.1\,\text{mg} \times 100\,\text{g}^{-1}$. These ascorbic acid contents were larger than the literature value of $15.2\,\text{mg} \times 100\,\text{g}^{-1}$. In this demonstration test, it is not irradiated with ultraviolet rays or blue light. Therefore, it can be inferred that production of antioxidants was promoted by environmental control by light, temperature, humidity, and hydroponics. In some herbs, it was inferred that it would be possible to add value by increasing the antioxidant content by environmental control in the plant factory. Besides that, basil produced at the center received a rating from the processor as being more fragrant than ordinary cultivated. In addition, cerfeuil was also evaluated as having a high aptitude for cooking because it is more fragrant than those marketed from French chefs. This suggests the possibility of promoting the production of aroma substances of herbs by environmental control in plant factories like polyphenols and ascorbic acid.

1.2.4 TECHNOLOGY TO INCREASE THE CONTENT OF FUNCTIONAL INGREDIENTS

1.2.4.1 Promotion of Synthesis of Functional Ingredients by Stress

As already indicated, polyphenols, carotenoids, and ascorbic acid are induced in their synthesis under stress conditions such that active oxygen is produced. In tomato, the addition of sodium chloride to the nutrient solution induces the synthesis of amino acids as a taste component [13]. In spinach, the synthesis of ascorbic acid is induced by ultraviolet rays or low temperature [14]. As such stress increases the production of useful components of plants, there is a possibility of increasing the value as a product by increasing the content of useful ingredients by applying stress. For this reason, if a plant factory that can freely control environmental conditions to some extent can promote the production of functional ingredients by environmental control, it is possible to improve the commercial value.

1.2.4.2 Technology to Increase the Content of Functional Components

As explained above, we believe that the easiest way to promote the synthesis of functional ingredients in plant factories is to irradiate blue light from ultraviolet rays with LED or the like. We have confirmed the phenomenon that the synthesis of anthocyanin is suppressed when water is cultivated with LED with less light of blue light (data not shown). We also confirmed that if strawberry fruits are irradiated with ultraviolet rays with LEDs at a fully artificial light plant factory, the content of anthocyanins and ascorbic acid increases (data not shown). Since it is also demonstrated that irradiation with blue light from such ultraviolet rays is good several days before harvesting (data not shown), ultraviolet rays and blue light do not affect the growth of the plants so much, and the processing expense will be low.

1.2.5 CURRENT ISSUES AND PROSPECTS FOR THE FUTURE

1.2.5.1 Current Issues

It is possible to promote the synthesis of polyphenols, carotenoids, and ascorbic acid by irradiating ultraviolet rays to blue light with LED or the like. However, it is unknown, ① at what time of the growth period, ② light of what wavelength, ③ light intensity, ④ how long irradiation should be done. With regard to ① to ④, the type of plant selected as a crop list at the plant factory and the same plant vary depending on the cultuvar. Optimization of such technology is possible by making an experimental plan that can perform statistical processing and quantitatively analyzing target functional ingredients.

1.2.5.2 Future Prospects

Herbs do not consume large quantities. Moreover, it is hard to say that it is rooted in Japanese food culture as a food ingredient. Therefore, as measures for expanding consumption, it is necessary for consumers to widely recognize that the content of functional ingredients such as antioxidants is increased, that the adhesion degree of microorganisms is low, and the content of nitrate ions is low. This makes it possible to distinguish herbs produced in plant factories from those cultivated normally. And think that this will add value and lead to an increase in unit prices. The functional ingredients are not just antioxidants. Many functional ingredients are possessed in vegetables and herbs, and many do not know how to induce these syntheses. Also, no method has been developed to conveniently quantify these functional ingredients. For example, scents are determined by combinations of many volatile substances and their concentrations, but the only way to conveniently quantify these is organoleptic test. Therefore, research on plant physiology or plant molecular biology such as what kind of functional ingredients can be induced by environmental control technology of a plant factory is necessary. At the same time, in order to shorten the time to practical use, it is also necessary to develop a simple analytical method for quantifying target functional ingredients. In the Netherlands, it was able to dramatically improve the yield of tomato in 20 years [15]. It has been breeding tomato specialized in cultivating in rock wool cultivation and sunlight utilization type plant factory. As special carrot varieties with high β-carotene content were produced, if specialized in cultivation in fully artificial light type plant factories and could produce varieties with high content of functional ingredients, it would be better to add value; I believe it will be possible.

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CHAPTER

1.3

Characteristics of Vegetable Growing in Plant Factories and Technical Issues

Hirokazu Fukuda[*], *Teruo Wada*[†]

[*]Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, Sakai, Japan [†]Graduate School of Life and Environmental Sciences, Osaka Prefecture University, Sakai, Japan

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1.3.1 VALUE OF PLANT FACTORY VEGETABLES

Many consumers think that "vegetables grown in the sunshine are more delicious." Under the light of the sun shining brightly, vegetables raised in fertile ground are tasty and sweet, especially when raised carefully in the hands of skilled farmers. However, customers who eat vegetables raised in a plant factory may be surprised. For example, many of the lettuce plants grown in a plant factory have good characteristics such as more freshness and softness and a smooth taste, so they are especially good for elderly people and children. Vegetables cultured in plant factories are novel and tasty products that differ from those grown outdoors.

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Deliciousness is constructed through the five human senses: visual, auditory, tactile, olfactory, and taste. Furthermore, various tastes depend on experiences from eating habits. Therefore, the color, crispness, scent, taste, and image of vegetables are all important to create commercial brands of a plant factory's vegetables. In this section, we will address the elements of deliciousness for vegetables, particularly lettuce.

1.3.1.1 Color

The color of lettuce changes not only with the cultivar, but also depending on the cultivation environment, such as the concentration of fertilizer, light intensity, and temperature. Therefore, it is possible to regulate the color of lettuce from pale yellowish green to dark green by controlling the environment, even for the same variety. Since the green color of plants is due to chlorophyll, if the amount of nitrogen and magnesium needed for synthesis of chlorophyll is limited, the green color of the leaf becomes pale, and if it is high, it becomes deep green. In a red-type lettuce, leaves turn red due to accumulation of anthocyanin. Recent studies have revealed that the synthesis and accumulation of anthocyanin are closely related to the proportion of red and blue lighting. It has also been reported that the expression of the genes *CHS* and *UFGT* responds sensitively to the intensity of blue light [1].

1.3.1.2 Crisp Texture

Plant factories have greatly accelerated the growth of vegetables compared to field cultivation. As a result, although fiber formation is somewhat inferior, the vegetables show positive features such as freshness and softness. Therefore, elderly people and children can benefit from choosing vegetables that are soft and easy to eat. However, depending on the variety and cultivation conditions, the crispness varies. Leafy-type lettuce, such as the Greenwave and Cos varieties, is a fresh and soft type of lettuce. Frill-type lettuce, on the other hand, has moderately firm leaves and a crispy crunch. In particular, "frillice" is a representative product of plant factories, as it is rarely cultivated in the field. The hardness of lettuce leaves can also be regulated by the concentration and/or composition of the nutrient solution and the light quality, for example, blue light.

1.3.1.3 Scent

Lettuce from a plant factory is moderate in smell compared with that cultivated in the field, but it is sometimes accepted as a less acrid one. The main chemical contributing to the grass-like smell is (E)-2-hexanal, which plays a role in defense against herbivores. Recently, it has been reported that this chemical acts as an inducer of abiotic stress-responsive gene expression, which includes inducing high temperature tolerance in plants [2]. Ethylene, a common volatile substance that acts as an influential plant hormone, has many effects including promotion of seed germination, suppression of stem elongation, and suppression of flowering. Therefore, it is presumed that volatile components from plants cause various physiological problems in plant factories. The investigation and effective utilization of such physiological effects will be addressed in the near future.

1.3.1.4 Taste

The components of taste are sweetness, acidity, saltiness, bitterness, and umami. These basic tastes are called the "primary tastes" because they cannot be made by any combination of other tastes. These taste components can now be measured by capillary electrophoresis (Fig. 1.3.1). For example, umami components are glutamic acid and aspartic acid, acidity is due to oxalic acid, citric acid and malic acid, and sweetness is evaluated by the levels of fructose, glucose, and sucrose [3]. In the evaluation of the taste components of lettuce cultivated in a sunny field or greenhouse, it is also reported that total phenolic content affects the sensory properties [4]. Lettuce also has a peculiar bitterness. When fresh lettuce is cut, a milky liquid polyphenol called lactucopicrin flows out, which is a bitter substance that acts as a light sedative and promotes sleep.

1.3.1.5 Image

Recently, a taste sensor and robots that respond like the tongue and nasal mucosa to various chemical substances have been developed. By comparing the pattern of the response potential in the sensor to the database, it is possible to output human sensitivity to the chemical substance. Thus, taste and response can be identified by machine. However, human preferences, whether likes or dislikes, depend strongly on personal feelings that are based on past eating experiences and mental images. No matter how tasty the food, it is difficult to overcome a bad image.

The image of vegetables grown in a plant factory is a big problem. Consumers generally have negative feelings toward the word "factory," which is associated with a mechanical setting like the manufacturing line of a food processing factory. However, it is rare for machines to be moving in a plant factory; vegetables just grow quietly on the cultivation shelves. In the cultivation room, only the soft sound of water flowing can be heard. It is not much different from how vegetables grow in normal greenhouse cultivation. A plant factory is so named because it can artificially control growing conditions and cultivate plants in an environment

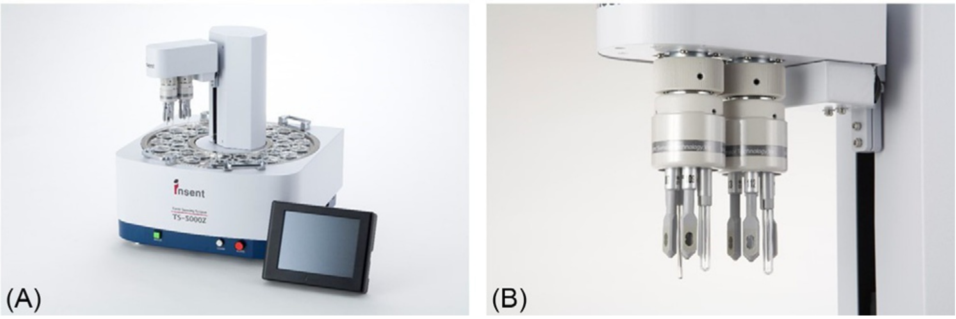

FIG. 1.3.1 Taste sensing system (TS-5000Z, Intelligent Sensor Technology, Inc. Japan). This system employs the same electro-chemical mechanism as that of the human tongue, converts the taste of various substances such as food and drugs into numerical data. (A) Appearance of TS-5000Z. (B) Teste sensors for bitterness, sourness, umami and saltiness of TS-5000Z. *Photos by Intelligent Sensor Technology, Inc.*

suitable for their growth, but it is different from the factories that people associate with manufacturing lines. The reality of the plant factory is not widely understood. The image of plant factories thus remains a big challenge. In the United States, the term "plant factory" is not used, but rather they are branded as "vertical farms," "indoor farms," or "indoor agriculture" [5].

1.3.2 SAFETY

Aside from taste, safety is the most important factor determining the value of vegetables [5]. Safety is assessed by factors such as the extent of contamination with insects, bacteria, soil, metals, and residual agricultural chemicals, ion concentrations in the plants, and concentrations of harmful metabolites.

In standard plant factories, insect infestation is controlled with double doors and air showers, work clothes are cleaned every 3 days, and pathogens are prevented by thorough washing with ozonated water and alcohol. As a result, since insects and pathogens do not usually enter, it is not necessary to use agricultural chemicals. In hydroponic cultivation, soil does not adhere to vegetables. As all incoming items are inspected by metal detectors, the risk of metal contamination can reach zero. These are standard specifications in plant factories, so their vegetables are safer than traditional vegetables. Since careful attention is also paid to the concentrations of ions and harmful metabolites, plant factory vegetables are very safe.

Plant factory vegetables are usually inspected at regular intervals for the number of both general viable bacteria and coliform groups. For examination of viable bacterial cells, the samples are homogenized with sterilized water, moderately diluted, mixed with a standard agar medium, incubated at 35°C for about 48h, and the number of colonies on the agar plate are measured. Generally, the number of general viable bacteria in plant factory vegetables is very low, at about 1/100 to 1/1000 that of field-grown vegetables. Plant factory vegetables have bacteria at a level of 10^3CFU/g or less, whereas field vegetables have about 10^6CFU/g. Therefore, plant factory vegetables are very safe and can retain high quality longer. To examine the coliform group, desoxycholate agar medium, BGLB liquid medium, and lactose broth liquid medium are used. For *Escherichia coli* examination, EC liquid medium is used, but none of these bacteria are normally detected in plant factory vegetables.

On the other hand, security can be potentially problematic. In order to achieve security, perfect implementation of the safety measures described above must be guaranteed. It is important to evaluate the safety of vegetables by examination for general viable bacteria and coliform groups and to evaluate the safety of nutrient fluids by assays for agricultural chemicals, heavy metals, and nitrate ions. In addition, it is essential to conduct screening and field surveys of operation-related documents and manuals to ensure reproducibility of safety measures. Currently in Japan, there are multiple safety certificates such as food safety ISO 22000, JGAP, and TPAC-PPS (a third-party evaluation and certification system for plant factory vegetables). Attainment of these is required for future security.

1.3.3 TECHNICAL ISSUES AND R&D

1.3.3.1 Solving Problems Associated With the Use of LED Light Sources

In plant factories, it has recently become more common to use LED light sources for cost savings and growth promotion, but they are not without issues. One is that tip-burn tends to occur under LED lighting, especially in lettuce and strawberries. In lettuce, it is generally understood that the reason is overpromotion of growth under the high light intensity. Methods to suppress tip-burn include distributing air flow around the growing point (e.g., shoot apex) during the light period and using a culture solution with high calcium and low potassium concentrations.

In the case of red lettuce, anthocyanin accumulation is not ideal when red LEDs are used. This might be due to the lack of ultraviolet (UV) light, which is a minor component in the spectrum of fluorescent lamps, but is absent in the red LED spectrum. Therefore, when cultivating red lettuce, it is necessary to include weak UV light.

Additional problems with the use of LED lighting have been identified. In raising seedlings such as tomatoes, a callus-like tissue may form in the leaves, which is called intumescence (swelling) or edema. It is sometimes reduced by UV irradiation, but the mechanism behind this reduction is not well-understood. In the case of spinach, leaves often warp or shrink under LED light. The occurrence of these deformations under LED lighting is higher than under fluorescent light.

When using LEDs as the light source, red light (about 660 nm), effective for photosynthesis, and blue light (around 450 nm) are typically used in combination at a certain intensity ratio. Recently, it was reported that a combination with green light (around 550 nm) enhances growth and increases the amount of certain compounds. A green LED with high brightness has been developed and is expected to be used for plant cultivation [5].

As an example of effects of the ratio of red and blue light intensity, height of plants generally increases under red-rich lighting. However, for certain vegetables such as strawberries, plants grow taller under blue-rich lighting. Therefore, the ideal red-to-blue ratio depends on vegetable type and variety, and it is necessary to conduct detailed systematic studies.

1.3.3.2 Issues Associated With Air Conditioning

As plant factories become larger, it is important to make uniform the conditions in their environment such as temperature, humidity, and air speed. For this purpose, arrangement of the air outlet and suction inlet of the air conditioner, air flow rate, arrangement of the shelves, and installation of crushed boards that induce ventilation flow have great influence. In a former plant factory (C21 building at Osaka Prefecture University, established in 2011), in a cultivation room with a height of 7 m, air flow directed up the wall and a ceiling vent to suck out the air, and the maximum temperature difference recorded between the floor and ceiling was 5°C. In an advanced plant factory (C22 building at Osaka Prefecture University, established in 2014), the installation of a duct system suppressed the temperature difference between the floor and ceiling to 3°C or less in the cultivation room, which has a height of 9 m. To model temperature distribution and air flow, simulations using computational fluid dynamics (CFD) are usually performed when the factory is designed, before construction;

however, correct estimations from simulations are difficult because a plant body has a complicated form that releases moisture by transpiration and changes as it grows. Although this affects resistance to air flow, the temperature also changes due to sensible heat and latent heat conversion and increased humidity, so numerical data due to the effect of plants cannot be sufficiently obtained in advance. Thus, simulation of the local atmosphere under plant cultivation conditions is challenging.

In plant factories with artificial lighting, theoretically, uniform growth can be achieved throughout the year, but the actual growth changes with seasonal variations in humidity. For example, in summer, the refrigerator of air conditioner stays in operation longer and then the humidity decreases. Conversely, in the winter, the refrigerator is used less and the humidity increases. In addition, although the relative humidity during the light period is supposed to be about 70%, in the summer it may decrease to about 30%. During the dark period, dew condensation occurs, especially in winter, and may cause deterioration of cultivation systems and electric systems.

For these reasons, it is important to evaluate the heat insulation performance of the outer wall, but it is also necessary to equalize the humidity in light-dark periods by dehumidification and introduction of outside air, having light and dark periods that coexist in the same cultivation room, and suppressing decreases in humidity during the light period using a high sensible heat type air conditioner (with a comparatively high temperature of the refrigerator and an air conditioner having a large air volume). However, in recent years, the amount of heat generation from the light sources in the cultivation room has been lowered due to the use of LED lighting, so reduction of humidity during the light period is not a significant problem with LEDs. Furthermore, late-night electric power is often used to lower the electricity cost, but coexistence of light-dark periods is also effective in reducing the peak electricity demand related to the basic charge and cost required for electric equipment.

1.3.3.3 Technology to Enhance Taste and Safety

Component analysis is necessary to evaluate the taste and safety of vegetables. As described above, the sweetness, umami, acidity, and other sensations that form the basis of taste can be directly measured by monitoring-related substances using capillary electrophoresis. Volatile substances that are components of fragrance can be quantified simultaneously using a gas chromatograph-mass spectrometer (GC-MS). For functional vegetables such as herbs, metabolites can be measured on a large scale using a liquid chromatograph-mass spectrometer (LC-MS). As an example of our research, when analyzing green perilla (*Perilla frutescens*) by an Orbitrap LC-MS (analyzed by Kazusa DNA Research Institute), 11,125 signals of metabolites including perillaldehyde, which is a harsh component peculiar to perilla, were detected (Fig. 1.3.2). By conducting simultaneous measurements of metabolites, harmful substances contained in vegetables, such as nitrate nitrogen, can also be measured. Therefore, not only the taste of vegetables, but also their safety can be analyzed comprehensively. It is thought that simultaneous measurement of metabolites (metabolome analysis) will become an important means for enhancing the taste and safety of vegetables.

As a method for evaluating the taste of vegetables, a taste sensor is attracting attention in addition to component analysis. There are hundreds to thousands of chemical substances to which the taste receptors respond, and the taste of a vegetable is recognized as a pattern of

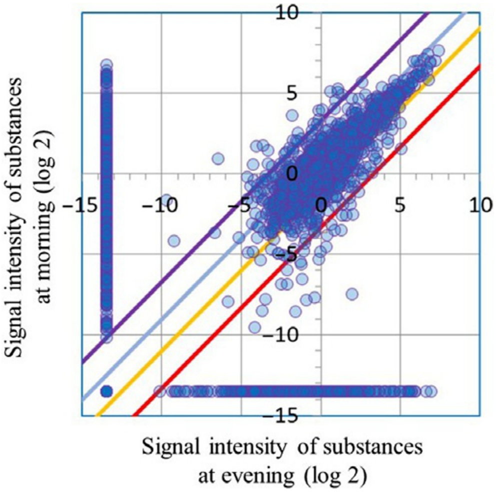

FIG. 1.3.2 Diurnal change of the signal intensity of 11,125 substances in a green perilla (*Perilla frutescens*). The purple, blue, yellow and red colored lines indicate that the signal intensity (the average of each signal peak from the LC-MS analyzer) at morning is relatively 10, 2, 1/2, and 1/10 times stronger than that at evening, respectively.

the taste of these substances. Therefore, it is difficult to evaluate taste only by measuring individual substances. The taste sensor imitates the human sense of taste and converts the concentration pattern of the chemical substances into taste information. Since it is possible to numerically evaluate the acidity, saltiness, umami, bitterness, astringency, and sweetness of vegetables, it is possible to obtain taste information that is easy for consumers to understand.

1.3.4 CONCLUSION

Vegetables in plant factories have big advantages because they are easy to eat compared with conventional vegetables, hygienic, safe, and secure. Safety can be advertised as a crucial advantage to consumers with proper management of hygiene and inspection of components if these practices are guaranteed by safety certifications. However, the higher the safety, the higher the cost, so development of management technology with reduced cost is required.

Plant factories are expected to further develop as a world food production technology. One of the challenges is to increase the reputation among consumers of vegetables grown in plant factories to the same level as traditionally grown ones. Especially, at the heart of Japanese traditional agriculture is the concept of seasonality, namely “in-season vegetables.” Establishing seasonality technology is an important goal in plant factories.

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CHAPTER

1.4

Postharvest Quality of Leafy Greens Growing in a Plant Factory

Celine C.S. Nicole[*], *M.P.C.M. Krijn*[*], *Udo van Slooten*[†]

[*]**Philips Lighting Research, Eindhoven, The Netherlands** [†]**Philips Lighting Horticulture LED Solutions, Eindhoven, The Netherlands**

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1.4.1 INTRODUCTION

Leafy greens are crops that are very suitable to be grown in plant factories. Among them are lettuce, arugula, and fresh herbs. Locally grown, these crops can reach the end-consumer faster, and therefore, the freshness can be guaranteed longer. For those crops which are usually sold minimally processed, it is important that the quality and food safety are fulfilled. Apart from reducing risks from bacterial load and other microorganisms, plant factories offer the possibility to grow these crops without pesticides. In addition, other quality aspects are requested such as appearance as judged from color and texture. For specific crops, taste is an important parameter and nutritional content as well (vitamins, flavonoids, carotenoids).

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For all the leafy green, shelf life is expected to be as good as with traditional horticulture practice. In a plant factory, because all the growth parameters are under control, this means the quality at harvest can be controlled as well [1, 2].

It has been questioned in the past whether growing in a totally controlled environment, without the natural environmental stress of climate and sunlight, enables the production of vegetables of similar quality as produced in more traditional horticulture growth. It has been shown that the choice of lighting quality or quantity may have a strong influence on the final product nutrient content [1–8]. In our research when using LEDs as the sole light source to grow vegetables, parameters such as light intensity, photoperiod, and spectrum must be optimized for each crop. We call this optimized prescription of a light recipe. This optimization of a light recipe is primarily aimed at maximizing the biomass production ($\mathrm{g\,mol^{-1}}$, also called light use efficiency (LUE)). It has been shown [4] that the LUE is one of the key performance indicators critical to the economic feasibility of a plant factory. Next to an optimized LUE, the quality should be optimized as well in order to differentiate in the market.

It is not obvious that a high quality can be achieved without compromising a high production. As an example, we show that the coloration of lettuce and the impact of shelf life on arugula could be improved without compromising the yield. In case of coloration (anthocyanin accumulation) in lettuce leaves, yield is shown to be correlated to the level of coloration. A new light recipe strategy was implemented for red-colored crops to maintain both a high production rate and a good final coloration. The light recipe used is named preharvest light and consists of changing the light composition and/or photoperiod a few days before harvesting the crop. A similar optimization strategy was also used to improve the vitamin content among other nutritional compounds in arugula and baby leaf spinach. Also, shelf life and taste of arugula grown under different light recipe spectra were measured. It was previously published that additional far red could improve the fresh weight to dry weight ratio in lettuce growth [9]. The effect on shelf life and taste was, however, not assessed. Light with a high fraction of blue has been shown also to have a strong effect on the metabolite content of some vegetables [6]; it is, therefore, expected to also have a strong influence on taste and shelf life [3]. We are showing here examples with arugula, basil, and lettuce that light quality (high blue or far red) and quantity (light level at preharvest) are both important in order to maintain a good product quality while growth efficiency remains high.

1.4.2 MATERIALS AND METHODS

1.4.2.1 Plant Factory

All experiments were carried out at the Philips GrowWise research center at the High Tech Campus of Eindhoven in the Netherlands. The total area for plant growth is $234\,\mathrm{m^2}$ and is distributed among eight climate cells with a four-layer system each with four sections, allowing many replicates with the same temperature and humidity conditions. The various climate cells are equipped with different types of LED lamps. Each cell contains four vertical growth layers. Each layer is split in four independently controllable light sections. The light level in some of the sections can go up to $600\,\mu\mathrm{mol/m^2/s}$. There is no significant temperature or humidity difference between the top and bottom layer in our experiments. The lighting systems we used in this work are the Philips Greenpower LED research modules which are spectrally controllable (blue, red, far red, and white) and dimmable. Each light section is calibrated in a defined rigorous procedure using a JETI spectrophotometer (Specbos 1201, JETI Tech. Instr. GmbH.). Seeds of red Oak lettuce and red Salanova were obtained from Rijkzwaan B.V. Seeds of basil (*Ocimum basilicum*), spinach (*Spinacia oleracea*), and rocket (*Diplotaxis tenuifolia* and *Eruca sativa*) were obtained by Enza zaden B.V. Rockwool substrate (Grodan) was used together with a standard nutrient solution in an ebb and flood system. The plant density during the germination phase was 1000 plant/m^2. Germination was under standard breeder's conditions with high humidity (>90%) and low light. During growth, irrigation was with a standard nutrient solution EC 1.7 to 2 mS/cm and pH 5.8 to 6. Lettuce and sweet basil are respaced at a later stage.

1.4.2.2 Plant Analysis

Plants' fresh and dry weight were measured at harvest (for spinach and arugula only the first harvest (first cut) has been analyzed). The chlorophyll and anthocyanin index of the leaves were measured using an optical device providing a relative index value in arbitrary units (DUALEX, Force-A, France). The analysis gives a qualitative indication of the effect of light on the content of pigments or compounds like chlorophyll. The total soluble solids (TSS) were analyzed using an optical refractometer giving the %Brix index of the plant harvested. Vitamin C and K content were analyzed by certified external laboratories. Vitamin C was analyzed by Masterlab Nutreco Nederland B.V. Quality determination was done visually using an overall quality assessment (OVQ) on a scale from 1 to 9 (starting score). The degree of yellowing, freshness and shininess, and smell were assessed as part of the OVQ. Harvested leaves were neither washed nor dried. For assessing the shelf life of baby leaf spinach and wild arugula, randomly selected leaves from 3 replicate growth batches were placed in 3 white plastic boxes (13 × 18 × 8 cm), bottomlined with a wetted filter paper to prevent dehydration. The boxes were closed with a transparent plastic lid with 10 small holes equally distributed to allow sufficient ventilation to prevent any depletion of oxygen or accumulation of carbon dioxide or other gases. The boxes were stored in a storage unit at 4°C in darkness.

A sensory analysis of arugula was performed. In this analysis, 30 untrained subjects, with an age range of 25–55 years old, both genders, volunteered to taste arugula salad for assessing the bitterness (including pungency), sweetness, and the flavor perceived by olfactory means and defined as the intensity of the aroma [10]. In case of sweet basil, we selected plants with similar ontogeny (number of pair of leaves) and selected the third pair of leaves for each plant and made three replicates which were frozen under liquid nitrogen and finely grinded. We measured the volatile organic compounds (VOCs) using a ppbRAE 3000 Volatile Organic Compounds sensor (RAE systems Inc., San Jose, United States). This sensor gives the total VOC content of a plant. The sensor was calibrated daily before use. For this protocol, a reference isobutylene gas at 10 ppm was used to calibrate the sensor and clean pressurized air was used as the zero gas. The measuring setup consisted of a glass box with a pressurized clean air inlet, two fans for air circulation. The inlet for the VOC sensor goes through a hole in the rubber cap that seals the glass box and the incorporated rubber glove allows to manipulate the samples inside the box. Samples were grinded just before, on site under liquid nitrogen, and maximum volatile count was measured while the temperature of the sample slowly increased to ambient (20°C).

Statistical analyses on nutritional content were executed for each crop individually, where the experimental repeats were collected from a pooled sample. Residuals were found homogeneously and normally distributed with Levene's and Shapiro-Wilk's tests, before being tested for statistical differences ($P = .05$) using One-way ANOVA and Fisher's LSD. Data were analyzed as in a randomized design, assuming no effect of location in the fully controlled climate cell.

1.4.3 RESULTS

1.4.3.1 Anthocyanin Accumulation in Red Lettuce

It is known from literature that a high level of blue enhances the production of anthocyanin [9, 11]. Using various red and blue ratios and increasing exposure, we have measured the anthocyanin accumulation for two different cultivars as a function of the total blue-daily light integral (blue-DLI) (see Fig. 1.4.1). Total PPFD was 180 μmol m^{-2} s^{-1} with a photoperiod of 18 h. Minimum blue percentage was 12% and maximum was 40%. We observed that a medium or higher blue dose increases the coloration depth, but not necessarily for all species. The color of Red Salanova seems to saturate as a function of the total blue-daily light integral, while the one of Red Oak lettuce does not. In addition, the effect of a high blue doses during the whole growth period reduces the final FW significantly (10%–20%) and makes the lettuce compact (see Fig. 1.4.2B). Blue doses should be optimized together with the total DLI and photoperiod. It is, therefore, important to optimize the growth and the coloration separately in time and adopt a growth stage-dependent lighting strategy to converge toward an efficient solution, and this should be done for each cultivar.

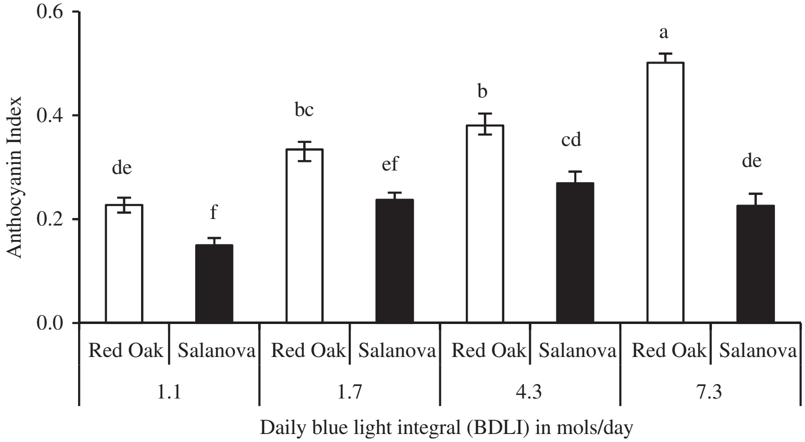

FIG. 1.4.1 Anthocyanin index as a function of blue light dose for the coloration of lettuce.

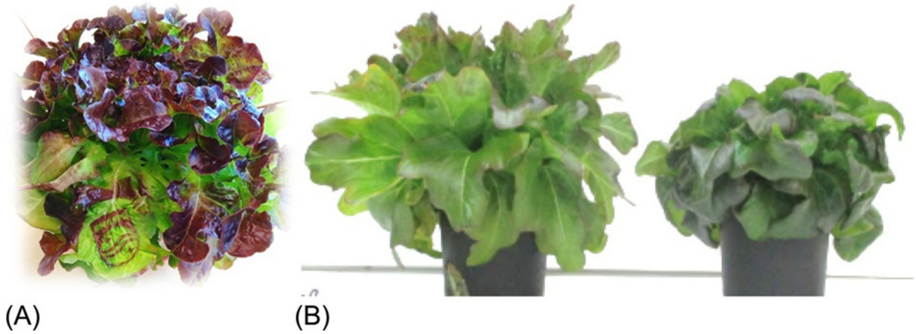

FIG. 1.4.2 (A) Red Oak lettuce after coloration and branding of a leaf with a logo. Accumulation of anthocyanin is locally achieved using a mask for a duration of 3 days under the coloration light recipe (50%R50%B) with an increased phot. (B) Salanova lettuce grown under RB (88%R and 12%B) and 25% far red (left) versus RB with 30% blue (right). Same cultivar showing strong morphological differences as a function of the light recipe.

Anthocyanin index was measured with Dualex scientific 4 fluorometer during harvest. Letters indicate significant differences ($P = .05$) within the same cultivar and control treatment (RW, RB).

From previous studies, we know that short wavelength radiation is particularly effective in stimulating anthocyanin biosynthesis, with UV light being one of the most promising light sources [12]. However, growing a lettuce with a low R/B ratio improves the coloration, but reduces the biomass. Therefore, we decided to explore growth stage-dependent light recipes and apply a lower R/B ratio only toward the end of the growth when the lettuce has almost reached its maximum growth efficiency to minimize any growth losses due to spectral changes. This is also called end-of-production light or preharvest light. In Fig. 1.4.3, we are

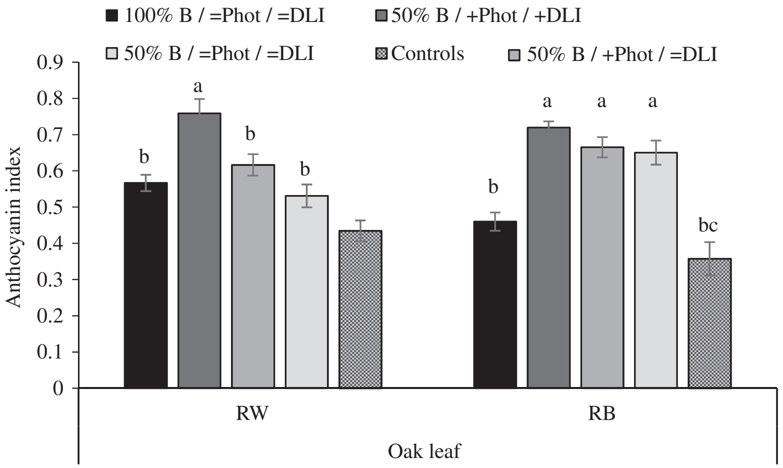

FIG. 1.4.3 Anthocyanin index of red oak lettuce after 5 days of preharvest lighting with different blue light fractions (%B; rest of light provided as red). 50% B preharvest treatments were conducted under 18 h (=Phot) and 22 h (+Phot) and different PPFD combinations, resulting into daily light integrals (DLI) equal (=DLI; 11.66 mol m^{-2} d^{-1}) or higher (+DLI; 14.26 mol m^{-2} d^{-1}) than used in the control treatments (RW, RB).

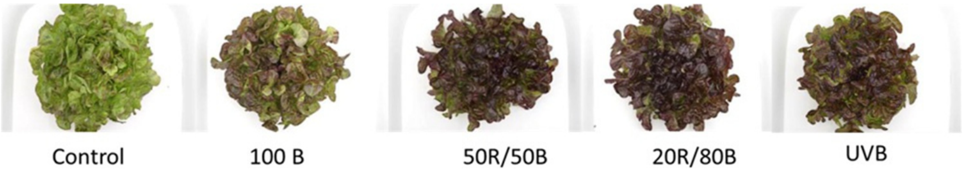

FIG. 1.4.4 Photos of the Red Oak lettuce under RW light (control) and preharvest light with 100% blue (100 B), 50% Red and 50% Blue (50R/50B), and 20% Red and 80% blue (20R/80B).

showing various preharvest light recipes for two different varieties. We are using either 100% blue or 50/50% R/B levels together with a higher or equal photoperiod (+ or = Phot) or higher or equal DLI (+ or = DLI). Preharvest light was applied up to 5 days before harvest, starting from an 80/20 R/B ratio for growth. Our results show that increasing the photoperiod and the DLI together with the blue dose seems to have the best effect on lettuce coloration. Also, our results show that 100% blue light is not necessarily the most efficient strategy to color a lettuce and that keeping a substantial level of red photons helps in the process (this was observed also recently by Owen and Lopez [12]). For several of our best dynamic growth strategies to color lettuce, efficiency did not worsen compared to the control, meaning that a growth stage-dependent recipe is an interesting strategy for a plant factory in maintaining a high g mol^{-1} performance. In a next step, it is also important to measure the long-term effect of such growth protocol on the shelf life and the influence on taste. Additional experiments have shown that using low doses of UVB light (Philips Narrowband TL/01) equally well results in an improved coloration of the lettuce at the end of the growth (see picture Fig. 1.4.4) compared to a preharvest treatment of 3–5 days using visible light. The UVB light level was applied as a sole light source for 90 min per day with an intensity of $0.36\ \text{W m}^{-2}$ at 311 nm, while the rest of the time the lettuce plants received the regular growth light recipe. This result shows that UVB performs equally well for coloring Red Oak lettuce compared to a combination of red and blue light. This experiment has been confirmed on two other lettuce cultivars of the Salanova type (results not shown).

1.4.3.2 Shelf Life of Products Grown in a Plant Factory

We investigated the main factors affecting the shelf life of vegetables by measuring and estimating the shelf life of baby leaf lettuces. Among all the factors affecting the shelf life, we have particularly looked at the light spectrum. Wild Rocket arugula was grown under three light recipes with a total DLI of $15\ \text{mol day}^{-1}$. Temperature was maintained at 26°C with a humidity around 75%. The first cut was harvested after 21 days and stored in individual boxes at 4°C in the dark. In this experiment, we have tested three drastically different lighting recipes, all being photosynthetically efficient (see Fig. 1.4.5). The control is a standard RW spectrum that we compare with a RB spectrum (36% of blue) and with a RWFr spectrum (with an addition of 25% Fr to the RW). At harvest, all wild arugula plants were in general having a deeper green color when the plants were grown without far red, or a higher fraction of blue light. The pale green color observed on the wild arugula grown under far red light could not be scored higher than 8 (maximum being 9) at harvest compared to the other plants (see Fig. 1.4.5); the color was visually significantly more light green than the other samples. This difference is maintained during most of the shelf life until the leaves decayed totally.

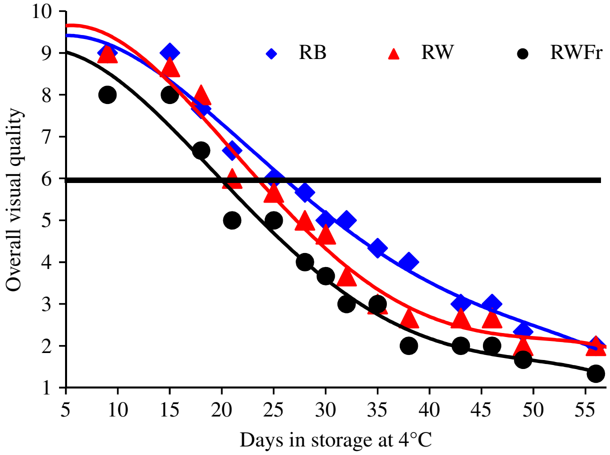

FIG. 1.4.5 OVQ of wild rocket grown under three different light spectra (RW, RB, and RWFr). OVQ crosses the consumer acceptance line at 20, 24, and 26 days. Each data point is the average of the OVQ of 3 individual samples.

The decay in the OVQ seems to follow the same trend for all light spectra; however, the starting quality difference makes the crossing with the consumer acceptance line very different (about 6 days) for the spectrum having far red. In terms of fresh weight, with far red, plants had a significantly higher yield (fresh weight) than RW and RB. High far red in the light showed also higher dry matter percentage (10% DM) compared to RB and RW (both 9% DM). Comparing different light recipes seems to affect the quality at postharvest. It is, however, questionable whether this quality change would be perceived by consumers when no comparison is possible in the retail shelves.

1.4.3.3 Taste of Vertical Farming Products

Sometimes, while the visual quality is difficult to assess, taste may play a more important role, especially for crops such as herbs and arugula which are strongly aromatic. We have carried out several sensory tests on arugula grown with three different light recipes (see Fig. 1.4.6A) with similar conditions as for the experiments on shelf life as described in the previous paragraph. Experiments on taste were done on both cultivated and wild types of arugula. The wild arugula has a stronger taste, and therefore, differences were difficult to detect with a nonprofessional and not well-trained taste panel. However, the cultivated arugula presented a change in taste as a function of growth light that was large enough to be detected by the nontrained taste panel. Besides, influencing the taste of cultivated arugula is commercially very interesting as this type is known to be poorer in taste compared to the wild type. In Fig. 1.4.6A, we are showing that the arugula (*Eruca sativa*) grown under the RB light had a significantly higher flavor intensity than the two other light recipes. Also, the effect of far red light was observed to influence more the bitterness and the sweetness. This experiment suggests that the aromatic composition may be influenced by the light recipe, suggesting that in the future we might be able to tune the taste of the final product.

A more quantitative experiment of taste is possible with the detection of the total amount of volatile organic compounds, using an electronic nose. This method is not very precise, but can help in rapid screening of species grown under different light recipes. A following step would

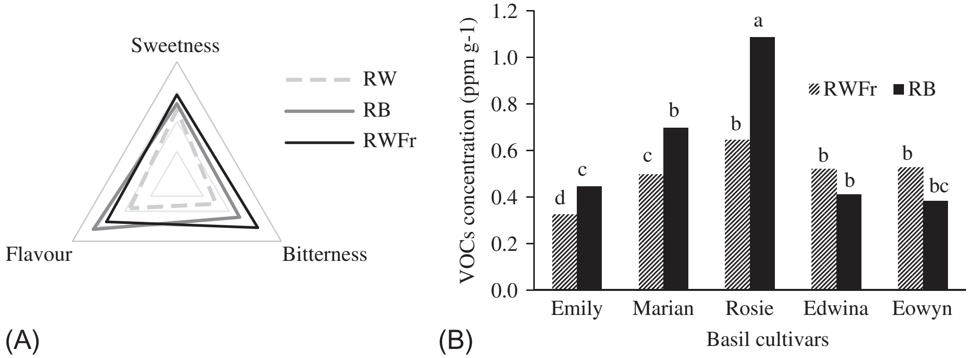

FIG. 1.4.6 (A) Taste measurement with 30 persons, within few days after harvest of cultivated rocket grown under 3 light recipes (RW, RB, RWFr). (B) Total volatile organic compounds measured for various sweet basil cultivars under RB and RWFr light.

include a deeper investigation measuring single volatile compounds to determine which are precisely influenced by growth conditions [3]. Several cultivars of sweet basil were grown under two light spectra, RWFr and RB at a DLI of 14 mol day^{-1} with a 16 h photoperiod. The total volatile count immediately after harvest varied significantly among cultivars and the light quality influenced the volatiles only for some of the cultivars, such as Rosie, Emily, and Marian (see Fig. 1.4.6B).

1.4.3.4 Nutrient Content of Vertical Farming Products

Vitamin C and other nutrients have been monitored in arugula and baby leaf spinach under different lighting recipes. Effects of the lighting spectrum (RW or RB with high blue) and a dedicated preharvest light treatment (Pre-RW or Pre-RB were the light remains continuously on several days before harvesting) are shown to influence significantly the concentration of nutrients in some cases. The preharvest treatment corresponds to continuous light for 2 days on baby spinach and 3 days on arugula. Samples were harvested and immediately frozen for analysis. Results are shown in Fig. 1.4.7. For baby leaf spinach, we observed that the highest vitamin C and K content is reached for RW light. A higher blue percentage is not favorable for most of the parameters measured except for the chlorophyll index showing higher values with high blue. Preharvest continuous light did not seem to influence the values for spinach either. In the case of arugula, the vitamin C content is higher with a higher blue percentage. However, this is not reproduced for vitamin K in which change remains not significant. The TSS and chlorophyll seem to benefit from a continuous preharvest treatment.

1.4.4 DISCUSSIONS AND CONCLUSIONS

We have shown that light may affect strongly the appearance of a lettuce crop. Far red and high blue levels are influencing strongly the compactness of a lettuce crop and its color. Despite having the PAR light level constant, the presence of far red during growth of red

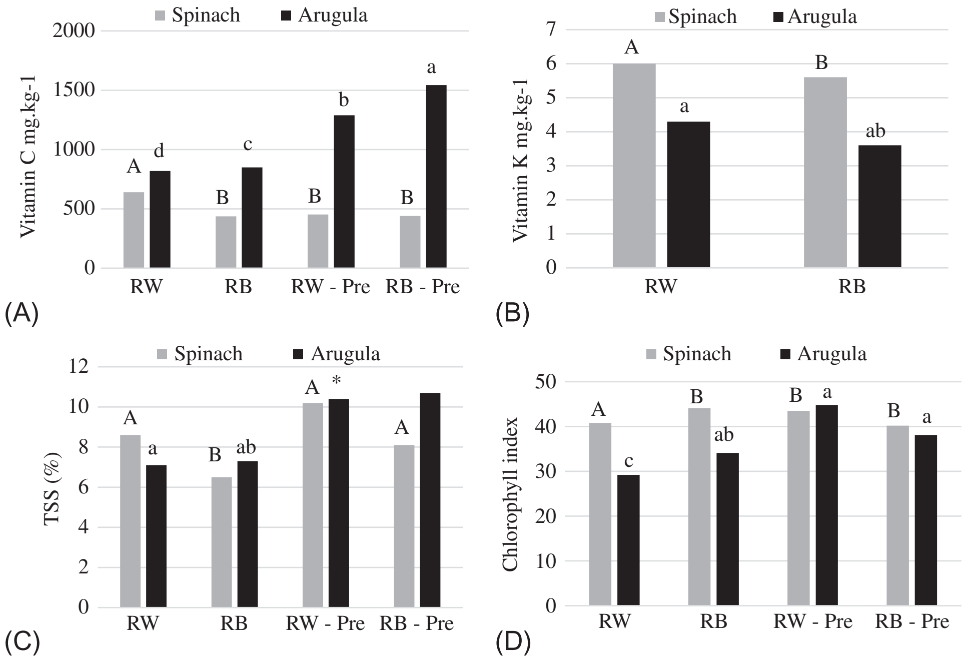

FIG. 1.4.7 Vitamin C (A), K (B), TSS (C), and chlorophyll index (D) of baby leaf spinach and arugula as a function of RW or RB light and with or without a continuous preharvest light treatment few days before harvest (2 days for spinach and 3 days for arugula). A statistical analysis is done per species separately.

lettuce seems to signal the plant to stretch and increase its light interception and building up less anthocyanin pigments. Van den Bussche et al. [15] found that far red light induces in arabidopsis plants an increase of leaf inclination upwards. Although we did not measure this parameter quantitatively, we systematically observed this effect on lettuce crops as given in the example of picture B in Fig. 1.4.2. In addition, it was observed on several crops that far red has a beneficial effect on yield [16]. Adding far red is, therefore, very tempting for improving production yield; however, some crops may express quality losses like coloration. The effect of far red on quality seems to be strongly cultivar-dependent. For example, a high dose far red induced less anthocyanin accumulation in our experiment by opposition to other cultivar described by Folta et al. [11]. A higher blue dose will have the exact opposite effect on morphology as far red does. Besides, it will increase compactness of the lettuce crop as was discussed previously in literature [13, 14]. Too high compactness is commercially not desired for a lettuce crop. However, the higher the blue dose, the higher the anthocyanin accumulation found. This confirms what was observed in previous work [9]. A high blue dose during the full period of the growth, however, reduces the biomass production [17]. It is, therefore, better to choose a lighting strategy that avoids yield losses. We have shown that with a preharvest coloration strategy, using for only 3–5 days an increased blue percentage (about 50%) with a simultaneous increase of photoperiod from 18 to 22 h has shown the best results for several lettuce varieties in improving coloration intensity, speed, morphology, and yield compared to control or other treatments [4]. For equivalent coloration achievement, our light recipe achieved equal yield (g mol^{-1}) compared to control.

While far red may increase fresh weight and improve morphology, we have shown that in the case of arugula the postharvest quality is negatively affected when plants are grown under far red. Shelf life was improved 6 days for arugula under the two extreme light recipes when stored at 4°C. While far red increased significantly the fresh weight, it reduced the postharvest quality. Far red should be used with caution during growth. With arugula, the treatments with higher blue percentages gave the best quality in taste and shelf life. Light recipes with high blue percentages also influenced the taste by increasing the total volatile compounds in several basil cultivars. This result was observed recently by Carvalho et al. too [3].

Nutrients content is influenced by light quality; however, each cultivar has its own optimum light recipe when choosing to optimize a specific parameter. Vitamin C (L-ascorbate) is modulated by light in plants [18]. In our experiments, the overall content of vitamin C and K were higher than the USDA [19] database values for both arugula and spinach. For vitamin C, reported values are 150 mg kg^{-1} for rocket and 280 mg kg^{-1} for spinach, while we observed a maximum of 1543 and 640 mg kg^{-1} respectively. Despite the data base numbers which do not distinguish between cultivars, several publications have shown that wild arugula could have values close to 850 mg kg^{-1} and for spinach 500 mg kg^{-1} in vitamin C content [7, 20]. It is difficult to compare nutrient content with regard to previous publications as authors used different analysis methods. What is remarkable is to have obtain so far, the highest vitamin C and K values measured in wild arugula. Those results being obtained in a plant factory condition, this means that nutrient content at high level can be controlled. This opens new opportunity in the food chain and marketing communication toward the consumer.

In conclusion, we have shown that, using different LED-based light recipes, we can influence considerably the postharvest qualities of leafy vegetables. We also observed that changes are strongly dependent of species and cultivars. There is, therefore, no universal lighting recipe for an optimum yield and quality at the same time. Fine tuning of plant factory lighting conditions needs to be done for each crop and set of quality attributes. Preharvest lighting recipes facilitate quality and yield on demand and would be relatively easy to adopt by a grower.

Acknowledgments

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CHAPTER

2.1

Nature and Source of Light for Plant Factory

Yong Xu

Centre of Excellence for Research in Optoelectronic Agriculture, Fujian Agriculture and Forestry University, Fuzhou, China

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2.1.1 INTRODUCTION

Light is one of the most important factors for plant growth and development, regulating plants' photosynthesis, morphogenesis, metabolism, gene expression, and other physiological responses [1]. The effects of light on higher plants can be characterized into the following

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two aspects: providing the energy required for plant photosynthesis and regulating the growth, differentiation, and metabolism of plants by lighting signals [2]. Effects of different light quality and intensity on the plants will be different. By adjusting the combination of light spectrum, it is not only simple to promote the growth and to control flowering and leaf shape of plants, but also possible to improve the concentration of functional chemicals in plants [3]. Combinations of light quantity, quality, and photoperiod can easily regulate plant's morphology, flowering, biomass accumulation and nutrient compounds, etc. [4]. The light available in plant lightings includes natural light and artificial lights, each of which has different properties and can be used for different purposes.

In this section of the book, we will first briefly discuss the general concepts and properties of electromagnetic radiation in order for the readers to be able to understand the contents that follow. Then two different methods of measuring light are presented in Section 2.1.3. A model of seven dimensions of light in plant lightings is discussed in Section 2.1.4. Sunlight is presented as the natural light and its attenuating factors are discussed in Section 2.1.5. Finally, artificial lights for plant lightings are discussed in Section 2.1.6 and conclusions are drawn in Section 2.1.7.

2.1.2 GENERAL CONCEPTS AND PROPERTIES OF ELECTROMAGNETIC RADIATION

Electromagnetic (EM) radiation is a form of wave, which can be characterized by speed c, wavelength λ, and frequency ν. The relationship among them can be characterized as

$$c = \lambda \cdot \upsilon \tag{2.1.1}$$

The speed of EM waves in vacuum was defined as a constant in the SI system of units in the 17th CGPM (The General Conference on Weights and Measures) in 1983, which is exactly 299,792,458 m s^{-1}, about 300,000 km s^{-1}. However, the travel speed of an EM wave in all other media is less than this figure. For example, the travel speed of light in a glass with a refractive index of $n = 1.5$ is 200,000 km s^{-1}. The wavelength describes the spatial period of the wave, which is the distance over which the wave's shape repeats, i.e., the distance from peak to peat or trough to trough. The frequency is the number of occurrences of the repeating wave per unit of time. The wavelength of the EM waves can range from subpicometer to a few thousand kilometers. The EM waves at different wavelengths range, or the spectrum range, are generally given different names and have different scope of applications. Fig. 2.1.1 shows the EM spectral distribution with visible light highlighted in which UV means ultraviolet, IR infrared, FM frequency modulation, and AM amplitude modulation, respectively.

We can see from this figure that visible light is only a tiny part of the whole EM spectrum, which ranges from 380 to 750 nm in wavelength and each color occupies a range of spectrum (where V represents violet, B blue, G green, Y yellow, O orange, and R red, respectively), i.e., it is not composed of a single wavelength. In plant lighting, only the visible light is the most effective spectrum range and, within the range of a specific color, the effect of different single or combination of wavelengths on plants may also be different. Therefore, to be exact, in a scientific report, the best way is to show the distribution of the spectrum or to give both

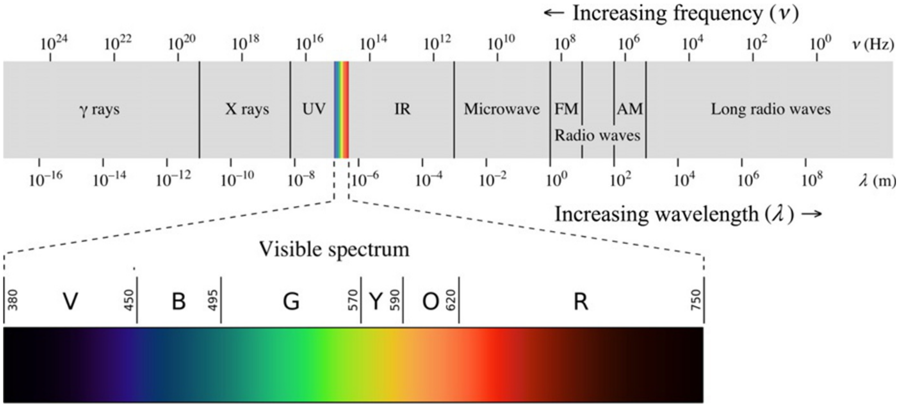

← Increasing frequency (ν)
10^24 10^22 10^20 10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4 10^2 10^0 ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^−16 10^−14 10^−12 10^−10 10^−8 10^−6 10^−4 10^−2 10^0 10^2 10^4 10^6 10^8 λ (m)
Increasing wavelength (λ) →
Visible spectrum
380 V 450 B 495 G 570 Y 590 O 620 R 750

FIG. 2.1.1 A diagram of the EM spectrum with visible light highlighted [5].

the peak wavelength and the half bandwidth of the color used in experiments in order for the author and/or other researchers to repeat the work in the future.

EM waves can be transmitted in vacuum, air, and many other different media. When an EM wave travels in a medium, some of the energy will be reflected, some absorbed, and some transmitted. The penetrating distance of the EM waves at different frequencies are different in different media, and sometimes, the speed is also different in different media. For example, the green and yellow lights and infrared light are easier to be reflected by or transmitted through the green plant leaves, but most of the ultraviolet, blue, and red lights are absorbed by them. Therefore, in plant growth with artificial lights, color of light should be carefully chosen to achieve the best lighting efficient. And the difference of light speed in different media is the cause of the rainbow.

In classical physics, the EM wave is generated when charged particles are moving in a variable velocity. For example, the radiation of TV signal is generated by the vibrations of free electrons in the TV transmitting antenna, infrared radiation by the vibration or rotation of the particles in the object, such as the molecules, and visible and UV radiation by the circulation of electrons around their nuclei, etc. The moving particles not only generate a changing electric field, but also a changing magnetic field. Therefore, the wave is composed of two perpendicular oscillating electric and magnetic fields, which are also perpendicular to the travel direction of the wave, i.e., the electric and magnetic fields and the propagating direction of the wave are at 90 degrees to each other. Furthermore, the two fields are always in phase to each other and the relationship among the three directions complies with the right-hand rule, i.e., if the fingers of the right hand are extended to point in the direction of the electric field and are then curled to point in the direction of the magnetic field, then the extended thumb will point in the direction of the wave, as is shown in Fig. 2.1.2.

In modern physics, an EM radiation is considered to be emitted and absorbed only discretely by one quantum after another, each of which is called a photon and has an energy E. Photons are the basic units of the EM radiation and all forms of EM radiation are made up of photons. A photon is a massless, indivisible, and stable particle and has no electric charge, which is generated by the transition of charged particles through different energy levels. When a charged particle transitions from a higher energy level to a lower energy level,

FIG. 2.1.2 The EM wave is a transverse one in which the electric and magnetic fields oscillate alternately with each of them vibrating on the plane perpendicular to each other and also to the direction of the propagation of the EM wave.

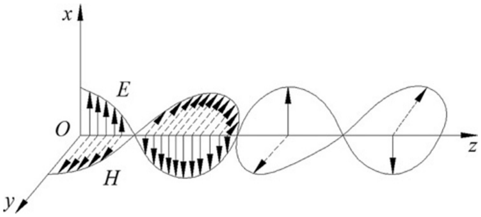
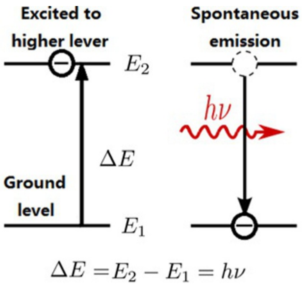


FIG. 2.1.3 When a charged particle transitions from a higher energy level to a lower energy level, it sends out a photon.



it sends out a photon (Fig. 2.1.3). The energy of a photon is given by the following Planck-Einstein equation,

$$E = h \cdot \upsilon = \frac{hc}{\lambda} \tag{2.1.2}$$

where $h = 6.626070040(81) \times 10^{-34}\,\mathrm{J\,s} = 4.135667662(25) \times 10^{-15}\,\mathrm{eV\,s}$ is the Planck constant [6].

In this way, the EM radiation would exhibit both the wave-like and particle-like properties, the so-called wave-particle duality of the EM radiation. When a photon propagates in space and passes through the length scale smaller than or equal to its wavelength, it displays wave-like phenomena. For example, a single photon passing through a double-slit experiment setup exhibits interferential patterns on the screen far away from it. However, when it is absorbed by or interacted with systems having the size of particles much smaller than its wavelength, such as a chlorophyll molecule or even the point-like electron, the photon acts as a whole and shows a particle-like property. Therefore, generally speaking, when the frequency of EM radiation is low (such as radio waves and microwaves), it mainly shows the characteristics of a wave. When the frequency is high, such as X and gamma rays, it is mainly characterized by particles. In the range of visible light, it exhibits the characteristics of both a wave and a particle. On the other hand, when an EM radiation propagates in space or interferes and diffracts, it is mainly characterized by the wave and, when it interacts with a matter, such as in the photoelectric effect and photosynthesis, it is mainly characterized by particles.

2.1.3 MEASUREMENT OF LIGHT

As the most effective spectrum for plant growth and development is around the visible light, we will mainly focus on this part of spectrum in the rest of this Section. The methods of measuring light include photometric, quantum and radiometric ones. In this section of the book, we only briefly discuss the first two methods.

2.1.3.1 The Photometric Method

For the visible light, the simplest way of measurement is done by using the human eye as the judging tool. This is indeed feasible and is called the photometric method, which is the science of measuring light in terms of its perceived brightness to the human eye. It is distinct from the radiometric method, a science of measuring radiant energy (including light) in terms of absolute power. In modern photometry, the radiant power in the spectrum of visible light at each wavelength is weighted by a luminosity function that models the average spectral sensitivity of human visual perception of brightness. This is generally characterized by the photopic and the scotopic luminosity functions (Fig. 2.1.4). In the photopic luminosity function, the maximum is at wavelength 555 nm, and in the scotopic function, at the 505 nm. As the photopic luminosity function is more commonly used, in the rest of this section, only this function is used.

In the International System of Units (SI), there are a number of photometry quantities, such as the luminous intensity, luminous flux, illuminance (or illumination), luminous emittance and the luminance, etc. We will briefly discuss these quantities in order to understand the basic concept of the photometry.

Luminous intensity is a measure of power per unit solid angle emitted by a point light source in a particular direction and weighted by the luminosity function, which is analogous to radiant intensity, an unweighted power intensity. The SI unit of luminous intensity is the candela (cd), which is one of the seven SI base units. As luminous intensity is analogous to radiant intensity, the candela is also analogous to the watt per steradian. In SI, a candela at frequency 540×10^{12} Hz (or at wavelength approximately 555 nm) is equal to 1/683 watt per steradian (sr), i.e., 1 w/sr at 555 nm is equivalent to 683 cd of luminous intensity. At other

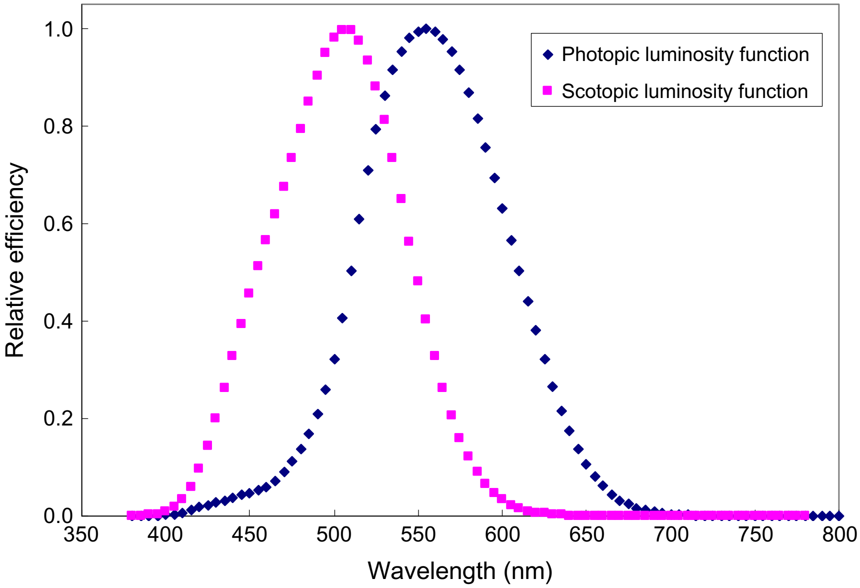


FIG. 2.1.4 The photopic (data from [7]) and the scotopic (data from [8]) luminosity functions.

wavelengths, 1 w/sr would be equivalent to fewer cd's of luminous intensity. For example, according to the luminosity function, 1 w/sr at 450 nm is only equivalent to 32 cd and at 715 nm to 1 cd of luminous intensity. Therefore, the farther the wavelength is from the center of the luminosity function, the weaker luminous intensity will be perceived per w/sr of light power.

Luminous flux is analogous to the radiant flux, a measure of the total power of EM radiation, but adjusted by the luminosity function. It is a measure of the total amount of light perceived by human eyes a light source sends out. The luminous intensity, however, is a measure of how bright the beam is in a particular direction. The SI unit of luminous flux is the lumen (lm). One lumen is defined as the luminous flux of light produced by a light source that emits one candela of luminous intensity over a solid angle of 1 sr. This unit is analogous to the unit of power, but adjusted by the luminosity function. Luminous flux is often used as an objective measure of the useful light emitted by a light source and the ratio of the total luminous flux to the radiant power is called the luminous efficacy of the light source. The higher the luminous efficacy a light source has, the brighter it is under the same power of light radiation.

Similar to the luminous intensity, at different wavelength, one watt of light power would correspond to different lumens of luminous flux. For example, 1 w of light power at wavelength 555 nm is equivalent to 683 lm, at 450 nm to 32 lm, and at 715 nm only to 1 lm. Therefore, the farther the wavelength is from the center of the luminosity function, the lower luminous flux will be perceived per watt of light power.

Illuminance is the total luminous flux incident on a surface, per unit area. It is analogous to the power density of the radiated light, but adjusted by the luminosity function. In SI-derived units, it is measured in lux (lx) or lumens per square meter ($\mathrm{lm\,m^{-2}}$). Similarly, luminous emittance is the luminous flux per unit area emitted from a surface, which has the same unit as the illuminance. The luminance is a measure of the luminous intensity per unit area of light in a given direction. The SI unit for luminance is candela per square meter ($\mathrm{cd\,m^{-2}}$). All these quantities are wavelength-related in terms of the power of light emitted from a light source.

2.1.3.2 The Quantum Method

The photometric method described above is based on human visual perception of the brightness of light and adjusted by the luminosity function. This is adequate for human activity-related lighting systems, but is obviously not suitable to plant lighting. There are three reasons for one to consider measuring the light in a different way when dealing with the interaction between light and plants. Firstly, plants "see" light differently from the human eyes. According to McCree [9, 10], there are two peaks in the distribution of absorption spectrum of higher plants, which is totally different from that of the photopic luminosity function. As lux is adjusted by the photopic luminosity function; it is definitely not a suitable measurement to determine the quantity of light available to plants. Secondly, when a light has a very narrow spectrum distribution, such as the light-emitting diode (LED), the lux calculated is generally distorted and useless for plants. For example, a red light at the wavelength 660 nm with a narrow bandwidth will have a relatively low lux. But it is very effective for plant's photosynthesis. Thirdly, unlike human eyes, which perceive light as continuous waves and therefore sense it as a continuous energy, plants perceive light as discrete photons and interact with it by absorbing the photons one after another. Therefore, the particle property of the light has to be considered and a different way of measurement has to be introduced. This is the quantum method in which the number of photons received by a receiver per second and per square meter is used to measure the photon flux density.

Assume that the spectrum density function of a light radiant flux density is $p(\lambda)$, where λ is the wavelength, the photon flux density perceived by a receiver can be written as

$$D = \int_{\lambda 1}^{\lambda 2} \frac{p(\lambda)}{hc/\lambda} d\lambda = \frac{1}{hc} \int_{\lambda 1}^{\lambda 2} p(\lambda)\lambda d\lambda \tag{2.1.3}$$

where λ_1 and λ_2 are the lower and upper bounds of the spectrum range and h and c are the Planck constant and the light speed, respectively.

As the energy of one photon is very small in terms of the ordinarily energy unit and the longer the wavelength, the lower the photon energy, a large amount of photons should be involved in order to have one joule of photon energy. For example, the energy of a blue photon with a wavelength of 450 nm is 4.4×10^{-19} J and 1 J of blue light would require 2.3 billion billion of such photons. Therefore, moles of photons should be used to describe such energy and one mole of particles is specified by the Avogadro's constant that equals 6.022×10^{23} particles. Nevertheless, the unit of mole is slightly too larger for the ordinarily energy and the unit of micro-mole of photons is generally used. Therefore, the unit for photon flux density is finally set as μmol photons m^{-2} s^{-1} and is generally simplified to μmol m^{-2} s^{-1}.

As photon flux density is related to radiant flux density, the relationship between μmol m^{-2} s^{-1} and w m^{-2} is given by

$$1\,\mu\text{mol}\,\text{m}^{-2}\text{s}^{-1} = 6.022 \times 10^{23} \times 10^{-6} \times \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{\lambda} = \frac{0.120}{\lambda}\text{w}\,\text{m}^{-2} \tag{2.1.4}$$

where the unit of wavelength λ is μm.

For blue light with a wavelength $\lambda = 450$ nm, 1 w = 3.75 μmol s^{-1}; for green light with a wavelength $\lambda = 550$ nm, 1 w = 4.58 μmol s^{-1}; and for red light with a wavelength $\lambda = 650$ nm, 1 w = 5.42 μmol s^{-1}. We can see from these calculations that the longer the wavelength is, the more photons would be required to produce 1 J of light energy.

On the other hand, as illuminance in photometry is the total luminous flux density in lux that is also analogous to w m^{-2}, but adjusted by the luminosity function, there must be a conversion between μmol m^{-2} s^{-1} and lux. But unfortunately, this conversion depends closely on the spectrum distribution $p(\lambda)$ of the light and there is no analytic expression for such a conversion. For different $p(\lambda)$, 1 μmol m^{-2} s^{-1} would result in different amount of lux and this difference is sometimes huge. The following lists the relationship between them for some typical light sources actually measured by us.

(1) The relationship between μmol m^{-2} s^{-1} and lux for solar light: 1 μmol m^{-2} s^{-1} $\approx$ 55 lx. This was measured in Fuzhou, China, in October at 3 p.m. This expression holds no matter whether it was under the direct sunlight, white cloud, or building shadow. This shows that the relative spectrum distribution of light under these conditions is similar.

(2) The relationship between μmol m^{-2} s^{-1} and lux for fluorescent light: This would be slightly different for different brand of lamps as there are different spectrum distributions. In our measurement, the relationship is: 1 μmol m^{-2} s^{-1} $\approx$ 70 ~ 75 lx.

(3) The relationship between μmol m^{-2} s^{-1} and lux for narrow-band LEDs: This would differ much for different colors of LEDs as there are totally different spectrum distributions for them. For blue light having a center wavelength 445 nm: 1 μmol m^{-2} s^{-1} ≈ 7 lx; for red light having a center wavelength 660 nm: 1 μmol m^{-2} s^{-1} ≈ 10 lx; for green light having a center wavelength 519 nm: 1 μmol m^{-2} s^{-1} ≈ 105 lx. We can see from these relationships that the farther the wavelength is from the center of the luminosity function, the more photons would be required to produce the same amount of lux.

From the relationships listed above, we can see that photon flux density in μmol m^{-2} s^{-1} and illuminance, the total luminous flux density in lux, are totally quantitatively different. Their relationship highly depends on the spectrum distribution of the lights. Therefore, the unit of lux cannot be used to measure the quantity of light absorbed by plants. The same amount of lux under different spectrum distributions would have totally different effects on growth and development of plants. Nevertheless, for the same kind of light having the same spectrum distribution, the unit of lux can also be used to compare relative light intensity. For example, the number of μmol m^{-2} s^{-1} for 5000 lx of sunlight is certainly greater than that for 3000 lx of sunlight. But it should be kept in mind that the number of μmol m^{-2} s^{-1} for 5000 lx of green light is no greater than that for 3000 lx of red light. It is sometimes even smaller than that for 500 lx of red light.

2.1.4 SEVEN DIMENSIONS OF LIGHT IN PLANT LIGHTINGS

The characteristics of light in influencing plant growth and development were generally attributed to three dimensions, i.e., the intensity, quality, and duration of light. The real situation could, however, be more complicated and may not be fully reflected by the above three dimensions. As plants are moved into artificially controlled environments in facility agriculture or as various kinds of artificial lights are used, the controllable and changeable factors of the light that can influence plant growth and development could be greatly increased and more dimensions of light must be considered. For example, apart from the intensity and spectrum distribution of light, polarization and coherence are among the most important features of light. In addition, uniformity of light distribution could be another factor to influence plant's responses. These additional factors would provide more opportunities for researchers to investigate the influence of light on plant growth and development. In this section of the book, a model of seven dimensions of light [11] will be discussed, which includes intensity, quality, pattern, uniformity, direction, polarization, and coherence. Each of these dimensions will be explained in detail in the following context.

2.1.4.1 Light Intensity

The light intensity in horticulture is a measure of the photosynthetic photon flux density (PPFD) and quantified as μmol photons m^{-2} s^{-1}, that is also simplified to μmol m^{-2} s^{-1} in the range of photosynthetically active radiation (PAR), which designates the radiation spectrum between 400 and 700 nm that higher plants are able to use in the process of photosynthesis [12]. As was mentioned before, there is no direct conversion between lux and μmol m^{-2} $s^{-1}$for different light sources and this is especially important in the design of artificial lighting in plant factories or supplemental lighting in greenhouses using narrow-band LEDs.

The importance of light intensity in promoting plant growth and development is very obvious and there have been many experiments that showed, under a certain extent, higher light intensity leads to higher plant yields [13, 14]. On the other hand, plants always have the effect of respiration and photosynthesis can only be carried out after the intensity of illumination has been increased to a certain degree. Photosynthesis and respiration are independent and interrelated processes and the balance of them is the compensation point of a plant's photosynthesis (see Fig. 2.1.5). When the intensity of light is lower than that point, respiration is stronger than photosynthesis; when the intensity of light goes higher, photosynthesis is stronger than respiration and increases almost linearly with the intensity of light. But as the intensity of light increases to a certain amount, the rate of photosynthesis would reach a saturation point and starts to decrease after that. Therefore, the best intensity of light would be in between the compensation and saturation points.

On the other hand, the unit $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ for PPFD involves a macro-quantity, the Avogadro's constant. That is to say, this is a mix of both macro and micro (the photon) quantities. In order to investigate the interaction between photons and the molecules in plants (such as chlorophylls) more precisely, we can convert this mixed macro-quantity into an entire micro-quantity by introducing the area of $(\text{nm})^2$. The conversion between $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ and $\text{phtons}\,\text{nm}^{-2}\,\text{s}^{-1}$ is as follows.

$$1\,\mu\text{mol}\,\text{m}^{-2}\text{s}^{-1} = 6.022\times10^{23}\times10^{-6}\times\left(10^{9}\right)^{2} = 0.6022\,\text{nm}^{-2}\text{s}^{-1} \tag{2.1.5}$$

That is to say, for every micro-mole of photons per square meter per second plants receive, there are 0.6 photons per second every square nanometer. As the size of nanometer is similar to that of the chlorophylls, by using the unit of $\text{photons}\,\text{nm}^{-2}\,\text{s}^{-1}$, we can easily estimate in average how many photons a chlorophyll would perceive at different PPFDs. Therefore, the unit of $\text{photons nm}^{-2}\,\text{s}^{-1}$ would be more meaningful in measuring the interaction between photons and the molecules, such as the chlorophylls, in plants.

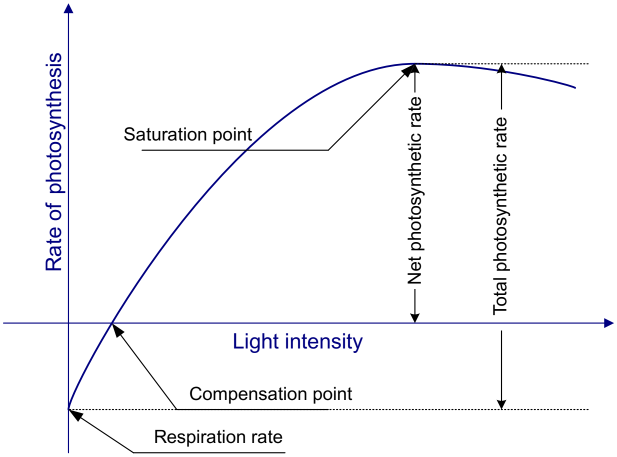


FIG. 2.1.5 Change of photosynthesis rate with the intensity of light.

2.1.4.2 Light Quality

Light quality refers to the composition of the radiation spectrum. It should be noticed that the same visual color might have different composition of spectra; hence, different light quality. Fig. 2.1.6 shows four different light sources having the same visual color of white, including two different brands of fluorescent lamps and two different combinations of LEDs. In plant-lighting experiments, the white light is often used as a control. We can see clearly from this figure that, due to their difference in spectral compositions, using different white light as a control will produce different results. Therefore, it would be more convincing if the spectrum distribution could be shown when a white light is used as a control.

Even for LEDs having a relatively narrow spectrum, the same visual color will sometimes have different spectrum distribution and/or different peak wavelengths. Therefore, just mentioning red or blue colors in a report is not accurate enough for other researchers to interpret and repeat the experiments. Showing the exact spectral distribution of the light used in the experiments would be beneficial to both the authors and other researchers alike for them to repeat the experiments in the future.

Light quality will induce various responses and play a decisive role in plant growth and development. Plant growth under the combination of blue and red light has been studied in detail [15, 16], which is effective in increasing plant biomass. But there are mixed reports on the effect of green light on plants. A report showed that the addition of green light to the blue and red light effectively enhanced lettuce growth [17]. Other studies indicated that adding artificial green light could induce stem elongation and reduce biomass in arabidopsis seedlings [18, 19]. In addition, the same plant in different growth stages would require different light qualities and a detailed study on this would improve both plants quality and yield.

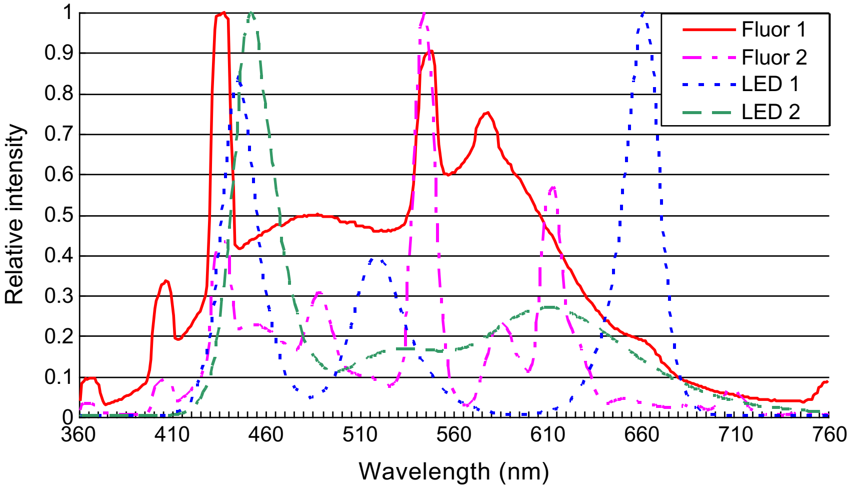


FIG. 2.1.6 Four different spectral distributions from lamps with the same visual color of white. Two fluorescent lamps (Fluor 1 and Fluor 2) and two different combinations of LEDs (LED 1 and LED 2) are shown [11].

2.1.4.3 Patterns of Illumination

The pattern of illumination is generally referred to as the duration of illumination or the periodicity of lighting. But in our definition, it contains much more complicated combinations of illumination modes. For example, instead of 12 h on and 12 h off in the 24 h period, it can be set to 1 h on and off, 1 min on and off, 1 s on and off, 1 ms on and off, 1 ns on and off, etc. alternatively for 24 h and plant responses among different illumination modes can be compared. As a scientific research, such change of illumination modes may lead to some valuable findings. Furthermore, for the color combination of red:blue = 7:3, instead of using a mix of 70% red and 30% blue at the same time, one can illuminate plants using red light for 70% of the time and blue light for 30% of the time, or using red light for 70% of the intensity all the time and blue light for 30% of the time at full intensity, etc. There could be many other possible combinations and this would cause some unexpected responses from plants and lead to some interesting findings.

We had used the following three modes to illuminate lettuce: A. 200 $\mu mol\,m^{-2}\,s^{-1}$ PPFD, 10 min on and off throughout 24 h; B. 154 $\mu mol\,m^{-2}\,s^{-1}$ PPFD, 13 min on and 7 min off throughout 24 h; C. 100 $\mu mol\,m^{-2}\,s^{-1}$, 24 h on. Under these modes, the energy density received by all the plants within 24 h is 8.64 $mol\,m^{-2}$. After 21 days of cultivation, we found that there were significant differences in the physiological parameters of lettuce, including total chlorophyll, chlorophyll a and b, carotenoid, MDA, VC content and plant height, dry weight, and fresh weight, etc. Fig. 2.1.7 shows the lettuce 2 weeks after illumination by A, B, and C modes. We can see from this figure that lettuce grown in mode C is the best, followed by A and B is the worst. Furthermore, as the light energy received by the plant in this period in the three modes is the same, we can conclude that the choice of illumination pattern has a significant influence on the growth of plants and there exists an optimal lighting mode to minimize the energy usage and at the same time maximize the output.

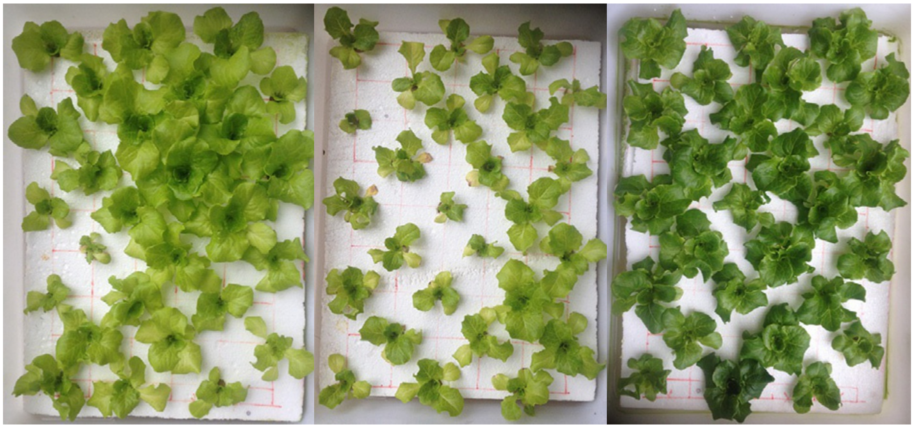


FIG. 2.1.7 Growth status of lettuce 2 weeks after illumination by A, B, and C modes. From left to right, modes A, B, and C [11].

2.1.4.4 Uniformity of Illumination

The uniformity of illumination includes that of the light intensity and the spectral distribution. In plant factory, it is a common practice for growers to use a combination of different color LEDs to implement a mixture of wavelengths. For example, a mixture of R:B = 8:2 is commonly achieved by arranging 8 red LED bulbs followed by 2 blue LED bulbs. This would, of course, lead to a nonuniform color and intensity distributions on the plants, which will not meet the designers' goals and will sometimes cause some stress reactions on the plants. Furthermore, even the most commonly used growth chambers having LED bulbs uniformly distributed on the top of each layer's roof would produce nonuniform illumination on the chamber. Fig. 2.1.8 shows the intensity distribution of light in a chamber with a size of 80 cm × 60 cm having 35 uniformly distributed LED bulbs on the roof. The height of the chamber is 40 cm and the distribution of light simulated is 35 cm from the roof. We can clearly identify that the intensity in the center is much higher than that on the edges. If there are a number of different colors of bulbs arranged alternatively on the roof, the situation is even worse. In older lighting systems with a number of fluorescent lamps on both sides of the chamber, it would arouse much more nonuniform distribution of illumination. Nevertheless, such kinds of growth chambers with either LED bulbs on the roof or fluorescent lamps on the

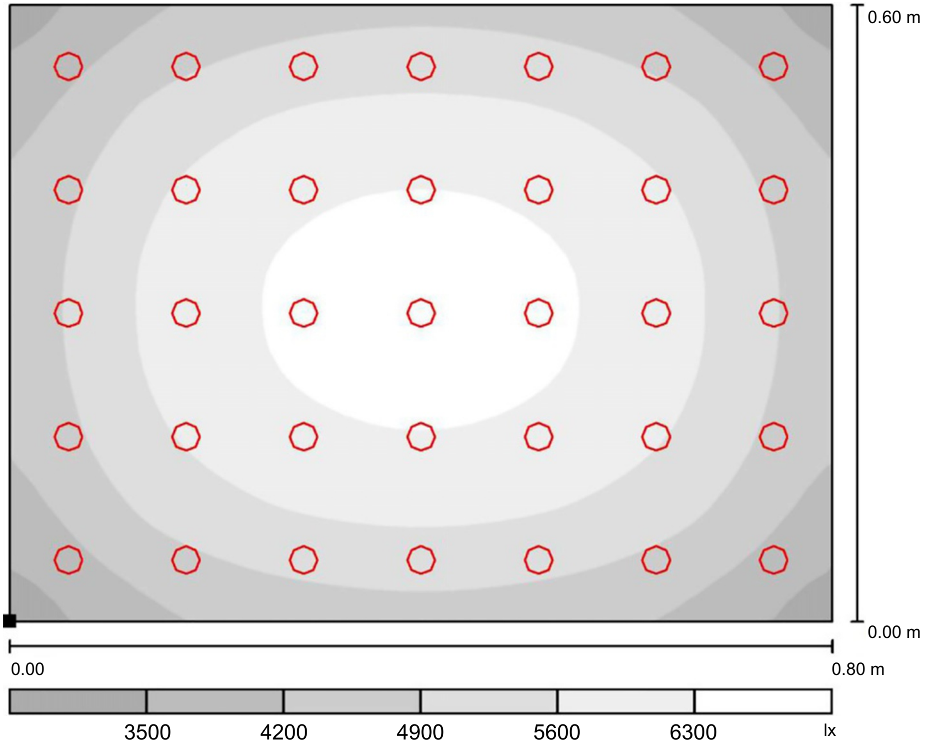


FIG. 2.1.8 The light intensity distribution in a growth chamber 35 cm from the roof with a size of 80 cm × 60 cm illuminated with 35 LED bulbs uniformly distributed on the roof [11].

sides have been used for decades to perform experiments. The results would be doubtful by whether the difference was caused by the nonuniform distribution of illumination or by the designed conditions the researchers would like to compare.

Nonuniform distribution of illumination either in light intensity or quality could cause plant stress and an extra energy consumption. We have used red and blue LED lights to cultivate lettuce separately and found that there was a significant difference between the biochemical parameters of the lettuce under these two illuminating conditions. But when we intentionally set up a nonuniform illuminating condition for the lettuce by illuminating one part of a lettuce using blue light and the other using red light at the same time, we found some interesting results. Our original purpose was to investigate the possible differences in these two parts of the lettuce illuminated by different colors of light. But it turned out that there was no significant difference between the biochemical parameters of lettuce in these parts. There should be a certain mechanism inside the plants to balance the different parts of it and this mechanism is not possible to be induced under natural conditions. Therefore, it is useful to investigate such mechanisms induced by the illumination of artificially nonuniform lights.

2.1.4.5 Direction of Light

Direction of light plants perceive can cause phototropism which enables plants to grow toward the light and blue-light photoreceptors called phototropins are primarily involved in sensing the direction of light [20]. Any nonuniformity caused by either light quantity or quality would also produce the response of phototropism in plants. Recently, great advances have been made in understanding the molecular, biochemical, and cellular bases of phototropism [21]. Therefore, investigating phototropism will enable researchers to reveal many aspects of plant growth.

2.1.4.6 Polarization of Light

As was mentioned in Section 2.1.2, light can be viewed as a transverse wave. In natural and most artificial lights, the electric and magnetic fields oscillate in all possible directions perpendicular to that of the propagation of the wave, i.e., there is no preferred oscillation direction. This is called the nonpolarized wave. If, by a certain means, the electric and magnetic fields could be deviated from this transverse symmetry and vibrated mostly in one direction, it is known as the polarized wave. If all the electric fields oscillate in only one perpendicular direction, this is referred to as the fully polarized light. Otherwise, it is called the partially polarized light.

As is shown in Fig. 2.1.9, apart from the major veins and ribs, there are still a lot of textures in the structure of a leaf. When it is illuminated by a nonpolarized light, some of the light would not be able to pass the textures. If it is illuminated by a polarized light and the polarization plane of the light could match that of the leaf's texture, the light would be absorbed by the plant more efficiently.

To the best of our knowledge, illuminating plants by polarized light has not yet been reported in the literature. However, studies and experiments have shown that polarized

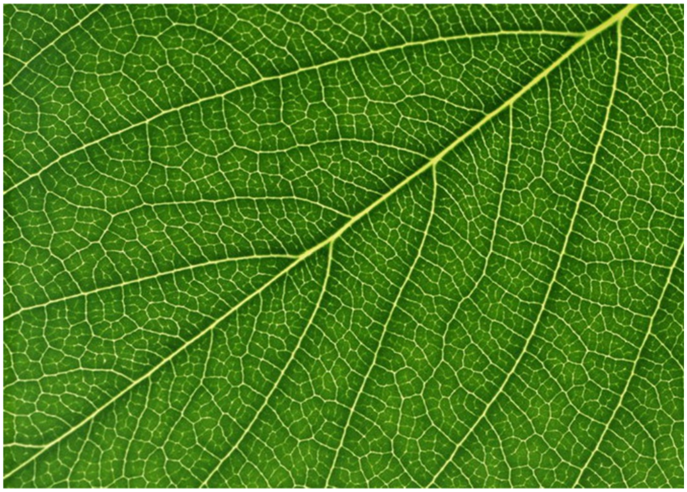


FIG. 2.1.9 The textures in the structure of a leaf.

red light is indeed more effective in eliminating various pains and relaxing muscles for humans compared with the nonpolarized light. Therefore, whether the polarized light is also more effective in inducing some responses in plants remains an interesting topic to uncover.

2.1.4.7 Coherence of Light

The natural light, as well as almost all artificial lights, including LEDs, are generated by spontaneous emissions, in which each photon is emitted from the light source independently through a transition from an excited state to a state with a lower energy, e.g., the ground state. As each photon does not have any relationship with others, such kind of light is called incoherent light.

The laser is an exception, in which the light is produced by a stimulated emission, feedback, and amplification. In such a process, a photon stimulated by another possesses the same oscillating state, i.e., both have identical phase, frequency, polarization, and direction of travel. Thus, the light emitted by a laser differs from other sources in that it is coherent. There are two kinds of coherence, the spatial coherence and temporal coherence. Spatial coherence is typically expressed through the output being a narrow beam, allowing a beam to be focused to a tiny spot or to stay narrow over a great distance. Temporal or longitudinal coherence implies a light beam with a very narrow spectrum, i.e., it has a near single wavelength or its phase is correlated over a great distance (the coherence length) along the beam.

An incoherent light beam has a very short coherence length, typically in the order of its wavelength λ [22]. Lasers, however, can have a coherence length as long as a few hundred meters. When plants are illuminated by a coherent light, there are two distinct features that are quite different from the incoherent one. The first comes from its spatial coherence. Due to the spatial coherence, the photons absorbed by the whole plant will exhibit the same phase, frequency, and polarization. The second is related to its temporal or longitudinal coherence. Due to its high longitudinal coherence and therefore long coherence length, a very long wave chain will be absorbed by the plants continuously. Whether some unique responses would be induced in plants illuminated by a coherent light are still yet to be uncovered.

There have been several publications showing that lasers, the typical coherent light, have great influence on plant growth and development [23]. However, none of the publications showed whether these effects were exclusively caused by lasers, especially, by laser's spatial or temporal coherences, or they were simply the common effects of the light. One research did show that higher final fresh weight was observed for the seedlings illuminated by laser. But the comparison was performed between a fluorescent lamp (with a wide bandwidth) and the laser (with a very narrow bandwidth) [24]. Nevertheless, a detailed comparison between the laser beam and ordinary light with the same peak wavelength and bandwidth would be interesting, which will be able to reveal whether the laser has a unique advantage in inducing some responses on plants over the ordinary light.

These are the seven dimensions of light we summarized in this section. By controlling these parameters of light, we may be able to find some new rules in plant growth and development under the artificially controlled environment.

2.1.5 SUNLIGHT AND ATTENUATING FACTORS

Sunlight is an EM radiation given off by the Sun, including mainly infrared, visible, and ultraviolet light. It provides almost all the energy required by all the creatures on Earth, including the plants. It was estimated that the annual potential of solar energy on Earth is $1.575–49.837 \times 10^{21}$ J. This is several times larger than the world's total primary energy supply which was 5.71×10^{20} J or 13,647 Mtoe in 2015 [25]. Although sunlight is usually not used in closed-type plant factories, it is the only source in photosynthesis in the natural light plant factories and in all other forms of plant cultivations. Therefore, we will briefly discuss it hereafter, especially the attenuating factors for the sunlight.

When sunlight hits the Earth, it is filtered through Earth's atmosphere and attenuated by various factors. Fig. 2.1.10 shows the solar radiation spectrum for direct light on both the top of the Earth's atmosphere (external region) and the sea level (internal region) and the corresponding blackbody radiation spectrum (solid line) at 5778 K (5505°C) [26], which is approximately the sun's surface temperature. When sunlight passes through the atmosphere, some of its energy is absorbed and some is redistributed by scattering. The most noticeable absorption bands by the atmosphere result from the absorptions of ozone (in the ultraviolet region), oxygen (in the near-infrared region), and water and CO_2 (in the intermediate- and far-infrared regions) molecules. Some other attenuating factors will be discussed below.

The first attenuating factor is the air mass coefficient, which is defined as the optical path length through the Earth's atmosphere, expressed as a ratio relative to the vertical path length, i.e., at the zenith. The greater the zenith angle of the incident sunlight, the larger the air mass and the weaker the solar radiation will be when passing through it. Larger air mass not only reduces the incident solar energy, but also changes its spectrum. Fig. 2.1.11 shows the solar radiation spectrum under different air mass [27]. Therefore, the spectral distributions of sunlight in the morning, noon, or afternoon are not the same, which will definitely affect plant growth and development.

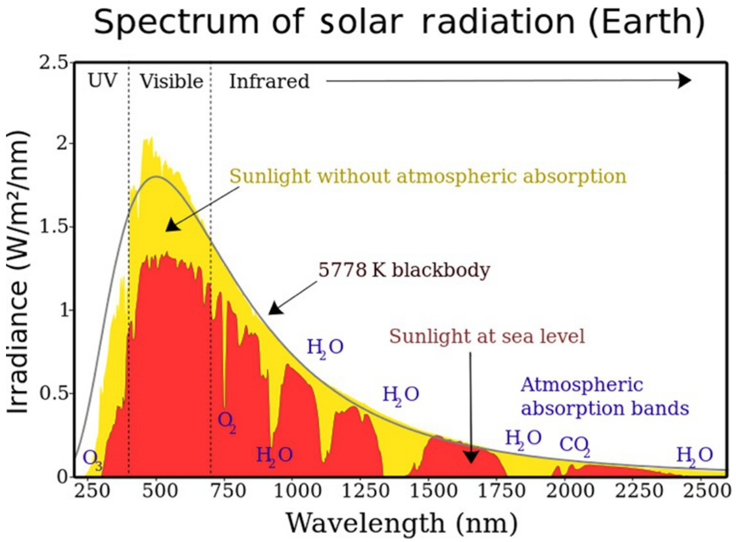


FIG. 2.1.10 Solar radiation spectrum for direct light on both the top of the Earth's atmosphere *(external region)* and the sea level *(internal region)* and the corresponding blackbody radiation spectrum *(solid line)* at 5778 K (5505°C) [26].

Another attenuating factor is scattering, including Rayleigh and Mie scattering. Rayleigh scattering is the elastic scattering of light by particles with a size much smaller than that of the radiation wavelength. The intensity of the scattered light is inversely proportional to the fourth power of the wavelength, i.e., the shorter the wavelength is, the stronger the scattered light is. This is why the sky looks blue in clear day. As the size of most dusts in the sky and the water droplets in the cloud is greater than the wavelength of visible light, this kind of scattering is generally caused by individual atoms or molecules. When the size of particles is greater than that of the wavelength of light, it causes the Mie scattering. Mie scattering is caused by a homogeneous sphere with a size greater than that of the wavelength of visible light. Dusts in the polluted air and water droplets in clouds are the major factors of Mie scattering and the intensity of the scattered light is independent of wavelength. Therefore, the polluted air has a look of gray and thin cloud is seen as white and heavy cloud as dark. As a result, the intensity of sunlight will be greatly reduced by either the heavy pollutant or thick cloud in the air.

Still, another attenuating factor is the absorption of ozone molecules. Ozone is a trioxygen, which forms an ozone layer in the lower part of the stratosphere, approximately 20–30 km above the Earth. Its thickness varies seasonally and geographically with a denser layer at the poles and thinner layer at the equator. Ozone filters out the UV radiations with wavelengths between 200 nm and 315 nm from sunlight so as to protect the creatures on the Earth from the damage by them.

2.1.6 ARTIFICIAL LIGHTS

As there is generally no sunlight available in closed-type plant factories or it is very expensive to guide sunlight into a closed-type plant factory, artificial light sources are widely used in these situations. Apart from plant factories, artificial lights are also used as a supplemental

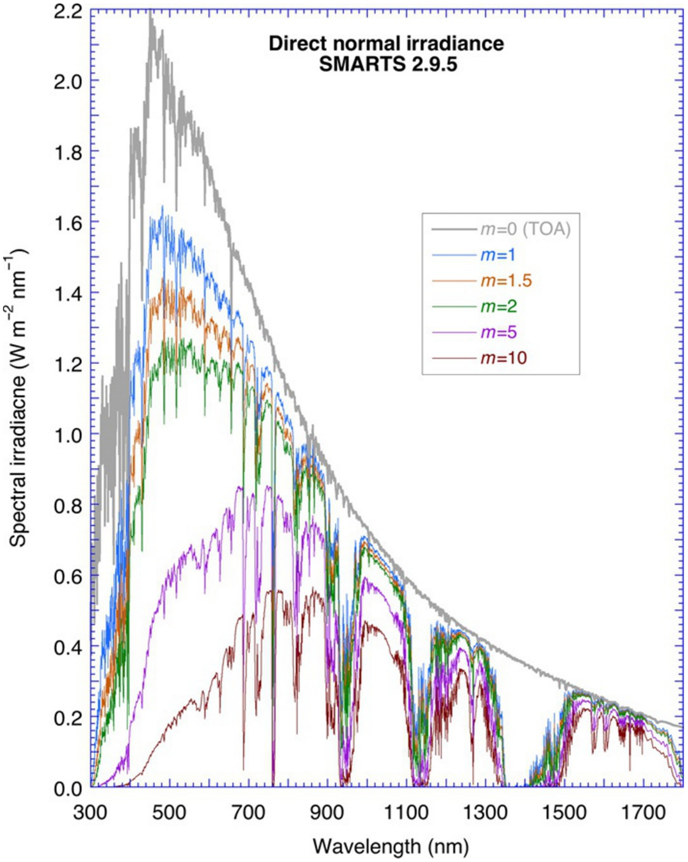


FIG. 2.1.11 Solar radiation spectrum under different air mass [27].

light in facility agriculture or in the situation when natural light is not sufficient to provide plants for appropriate photosynthesis. For example, when the available time of daylight is not long enough in the winter months, or when there are a number of consecutive raining days or when there is a heavy air pollution so that the light intensity is not strong enough for plants to grow healthily, artificial supplemental lights are required either to extend the lighting time or to increase the lighting intensity or both.

In early days, it was thought that a light with a spectrum similar to that of sunlight is the best for plant growth. For this purpose, a light with a wide spectrum should be used. But now, it is found that not all spectra are equally important for the benefit of plant growth [19]. Therefore, artificial lights are now generally designed to provide a spectrum that is more suitable for the needs of the plants being cultivated. For this purpose, an adjustable combination of narrow-band light-emitting diodes (LEDs) should be used to provide different plants at different growth stages with different light intensity, quality, and duration.

In this subsection of the book, we will briefly discuss some types of artificial light sources that are commonly used in plant lightings for various purposes. Before that, we need to elucidate some concepts related to the light sources.

2.1.6.1 Luminous Efficacy, Photon Efficacy, and Light Efficiency

Luminous efficacy is a measure of how well a light source produces visible light. It is the ratio of luminous flux to power, measured in lumens per watt (lm/w) in the International System of Units (SI). According to how the power is measured, there are two different definitions for it. The first is given in Section 2.1.3.1 in which the power is the total radiation from the source. This is also called luminous efficacy of radiation and the maximum possible value of it is 683 lm/w for the monochromatic light at a wavelength of 555 nm. The second uses the total power consumed by the source, either electric, chemical, or other forms, as the "power." This is also called luminous efficacy of a source and the maximum possible value of it is smaller than 683 lm/w. In this section of the book, we will use the second as the definition of luminous efficacy so as to express how much of the consumed power can be converted into visible light. For a light composed of multiwavelength, it's efficacy is always smaller than 683 lm/w.

Photon efficacy in this book is defined as the Photosynthetic Photon Efficacy (PPE), which is the ratio of photosynthetic photon flux to power with the unit of μmol photons s^{-1} per watt (μmol s^{-1}/w). Similar to luminous efficacy, there are also two kinds of definitions for it according to how the power is measured. The first is called the PPE of radiation that uses the total radiation from the source as the power and the maximum possible value of it is $(\lambda/0.12)$ μmol s^{-1}/w for a monochromatic light with a wavelength λ in μm. The other called the PPE of a source uses the total power consumed by the source, either electric, chemical, or other forms, as the "power" and the maximum possible value of it is smaller than $(\lambda/0.12)$ μmol s^{-1}/w for a monochromatic light with a wavelength λ in μm. For a light composed of multiwavelength, it's efficacy is equal to or smaller than $\int_{\lambda 1}^{\lambda 2} p(\lambda)\lambda/0.12 d\lambda$ μmol s^{-1}/w, where $p(\lambda)$ is the spectrum density function of the light and λ_1 and λ_2 are the lower and upper bounds of the photosynthetically active radiation, respectively.

Light efficiency is defined as the ratio of the total light power to the total power. According to how the light power and the total power are measured, there are four different definitions for it. The first is the visible light efficiency of radiation in which the light refers to that in the visible region and the total power is the total radiation from the source. The second is the photosynthetic light efficiency of radiation in which the light refers to that in the range of photosynthetically active radiation (PAR) and the total power is the total radiation from the source. The third is the visible light efficiency of a source in which the light refers to that in the visible region and the total power is that consumed by the source. The fourth is the photosynthetic light efficiency of a source in which the light refers to that in the range of PAR and the total power is that consumed by the source. In all these definitions, the light efficiency is always a dimensionless quantity. According to different application situations, different definitions should be used. In this section of the book, we will use the third as the definition of visible light efficiency and the fourth as that of photosynthetic light efficiency so as to express how much of the consumed power can be converted into the corresponding light.

2.1.6.2 Incandescent Light

Incandescent light is generated with a filament inside a bulb heated by electric current to a high temperature so that it glows to send out visible light. The spectral distribution of an incandescent light is similar to that of the blackbody. As the temperature of the filament inside the bulb (typically less than 3000 K) is much lower than that of the sun (about 6000 K), most of the radiations are in the infrared region with only a small part in the visible one. The typical luminous efficacy of incandescent light is only 10–15 lm/w with a lifespan generally less than 1000 h. Therefore, the plant-lighting efficiency is very low and it is generally not used for plant lighting now.

2.1.6.3 Fluorescent Light

Fluorescent light is generated by a low-pressure mercury-vapor gas-discharge lamp in which the ultraviolet light is produced by the excited mercury vapor that causes a phosphor coated on the inside of the lamp tube to send out visible light. As such, the spectrum of a fluorescent lamp is the combination of that of the mercury-vapor emission and the fluorescence of the phosphor. The relative intensity of light emitted by each component is dependent on the thickness of the phosphor coating. Depending on the types of the phosphor, there are different visual colors of the fluorescent lamp. Fig. 2.1.12 shows the spectral distribution of two different white fluorescent lamps, both of which are made by Philips. In this figure, the emissions with wavelengths 404.7, 435.8, 546.1, and 579.0 nm come from the mercury vapor and other parts of the emissions are from different type and thickness of phosphors.

Depending on the type and the thickness of the phosphor, the typical luminous efficacy of fluorescent lamps is 50–100 lm/w, which is much higher than that of the incandescent lamps. Furthermore, by choosing the appropriate type and thickness of phosphors, the spectrum of a fluorescent lamp can be tailored to provide the needs of the plants to grow more quickly and strongly. Another advantage of this type of lamp is its long lifespan in the range of 24,000 h. Therefore, the fluorescent lamp is a better artificial light source than the incandescent lamp for plants.

2.1.6.4 High Intensity Discharge (HID) Lights

HID lights refer to a set of lights including mercury vapor, metal halide, high-pressure sodium (HPS), and the conversion bulbs. A mercury-vapor lamp uses an electric arc as a gas

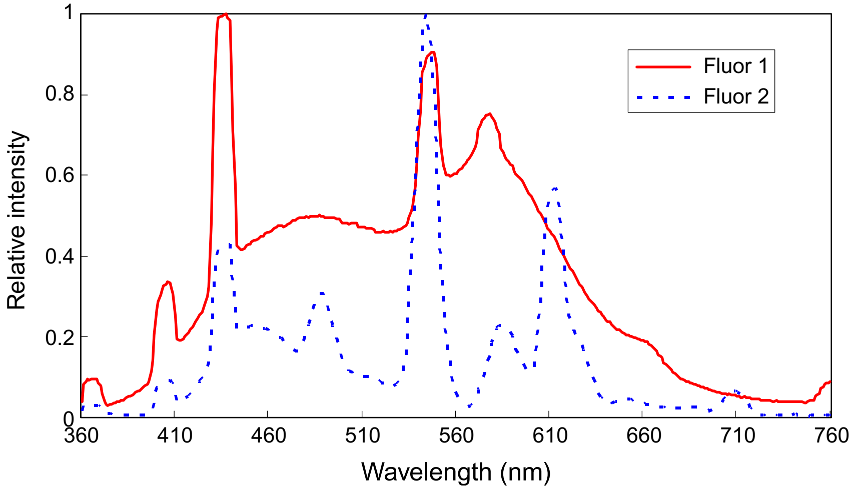


FIG. 2.1.12 The spectrum of two different white fluorescent lamps.

discharge through the vaporized mercury to produce light. There are two types of mercury-vapor lamp with the outer bulb clear or coated with a phosphor. Depending on the pressure of the mercury vapor inside the bulb, the former can produce different spectral distributions but it is not suitable very much for plant lighting as most of the spectra do not match any plant and the later works exactly like the fluorescent lamp does.

Slightly different from the mercury-vapor lamp, a metal-halide lamp uses an electric arc in the quartz arc tube as a gas discharge through a mixture of vaporized mercury and metal halides gas. Metal-halide lamps also have high luminous efficacy of around 75–150 lm/w and a lifespan between 6000 and 15,000 h. Depending on the components of metal halides and the gas pressure inside the tube, the spectral distribution of the metal-halide lamp is slightly different. But they generally have a wide spectrum that mimics the color spectrum of sunlight, and hence, provides a high color rendition. As a result, they are widely used in commercial, industrial, public, and residential security lightings, and as automotive headlamps. They are also one of the most popular options for outdoor plant lightings, although their spectrum does not match that of the plant very well. For indoor plant lightings, as metal-halide lamps produce a large amount of heat, they are generally replaced by other types of lamps.

High-pressure sodium (HPS) lamps work slightly differently from other HID lamps in which a small amount of neon and argon gas is used to start the gas discharge. When the discharge started, it emits a dim red/pink light to warm up the sodium metal. As the sodium metal starts to vaporize after a few minutes, the emission sends out the visible light. HPS lamps have a luminous efficacy of 100–150 lm/w and a lifespan also between 6000 and 15,000 h. The HPS lamp also has a wide spectrum, although the specific distribution of it depends on the gas pressure inside the tube. The range of applications and suitability as a plant-lighting source are similar to that of metal-halide lamps.

2.1.6.5 Light-Emitting Diodes (LEDs)

Unlike all the lamps described above, a light-emitting diode (LED) is a solid-state semiconductor light source. It is composed of a p-n junction that emits light when electrical current is applied to recombine the electrons and the holes within the junction. In this process, energy is released in the form of photons and the color of the light is determined by the energy band gap in the junction. Typical lifetime of a single LED is 25,000–100,000 h, which is much longer than that of the lamps discussed before.

Single LED can only emit narrow-band light. In order to produce a broad-spectrum light, two primary ways are generally used. One is to use individual LEDs that emit different colors with different intensities and then mix all the colors to form a broad-spectrum light. The other is to use a phosphor material coated on the top of a monochromatic short-wavelength LED, usually a blue or UV LED, to convert the narrow-band LED light into a broad-spectrum light, in much the same way a fluorescent light bulb works. Fig. 2.1.13 shows an example of the white spectra generated by these two methods where the spectrum marked LED1 is generated by the first method and LED2 the second. Depending on the methods used, the luminous efficacy of a white-colored LED ranges from 150 to 300 lm/w, also much higher than that of the lamps discussed before.

LEDs have many advantages over other artificial light sources, including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster

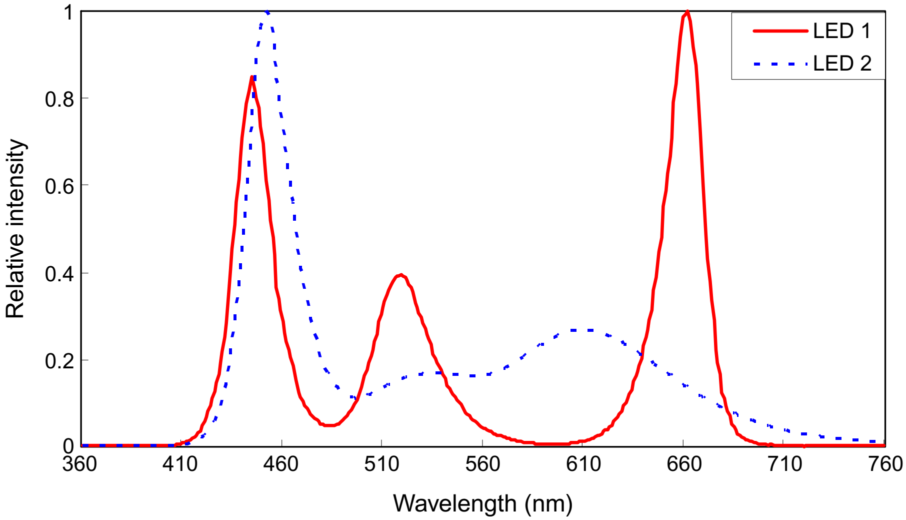


FIG. 2.1.13 An example of the white spectra generated by the spectra mixture (LED1) and the fluorescent (LED2) methods.

switching. The most important features of LEDs for plant lightings are their narrow bandwidth and easy adjustability, which ensure the high purity of monochromatic light and the arbitrary combination of them to suit any plant at any stage. By an appropriate control of monochromatic LEDs in a combined LED lighting system, it is even possible to use the light to trace the growth of plants so that the lighting combination is always the optimal in the whole process of their growth. Therefore, it is no doubt that LEDs are the most promising source for plant lightings. Metal halides and other artificial lighting sources will gradually be replaced by LEDs as the technological improvements and price declinations.

2.1.6.6 Lasers

A laser differs from other sources of light in that it emits light through a process of light amplification based on the stimulated emission of EM radiation. Light emitted by a laser is spatially and temporally coherent with monochromatic color at nearly a single wavelength. There are different types of lasers, including gas lasers, such as the helium-neon laser and CO_2 lasers, solid-state lasers, such as the first invented ruby laser and Nd:YAG lasers, liquid-state lasers, such as dye lasers, and the semiconductor lasers (also called the laser diode, LD), etc. Different types of lasers have different scope of applications. For plant-lighting purpose, laser diodes are the most promising ones due to their high efficiency, low cost, large variety of available wavelength, and long lifetime.

Lasers have been widely used in many applications owing to their advantages of coherence, including optical disk drives, laser printers, barcode scanners, optical communication, surgery and skin treatments, cutting and welding materials, marking targets and measuring range and speed, etc. Recently, lasers have been used for lighting purposes by using the two primary ways similar to that described in Section 2.1.6.5 to combine lasers with different colors to form a desirable spectrum. Although lasers are not widely used in plant lightings by now, it is easier to combine monochromatic color lasers to form an optimal spectrum for plant growth. With the price gradually cut down and more colors available, we believe that lasers will be used in plant lighting more and more commonly due to their unique advantages described in Section 2.1.4.7.

2.1.7 CONCLUSIONS

"God said, 'Let there be light,' and there was light." (Genesis 1:3) Light is the priceless gift given to us by God that is the only source continuously supplied to and endlessly accumulated by the Earth to maintain the existence of all forms of life on it. Light itself also has many useful properties that can be applied to plant factories and many other situations for various plant-lighting purposes. For production purposes, only the first three dimensions are important in the seven dimensions of light. The appropriate combination of light intensity, quality, and pattern should be able to provide for the plants to grow faster and healthier and to accumulate useful biochemical compounds easier for different application purposes. I was also told that by using a very low intensity of blue and red laser as a supplemental light in the evening, the plants would grow faster and stronger compared with those without such supplemental light. As I did not actually see the experiment, the interested readers can try for themselves. For research purposes, the appropriate combination of the seven dimensions of light would be able to bring about some interesting findings that would never be seen before.

As for the choice of artificial light in plant factories, we recommend to use LEDs due to their many advantages over others. In order to reduce the usage of lighting energy, careful experiments should be done to find the optimal combination of the three dimensions mentioned before. The technique of growth-tracking by light could also be used to ensure that the light mode is always the optimal at all stages of the plant growth. Uniformity of illumination should also be paid attention to in order for the plants to grow more evenly and at the same time to save energy. Although LEDs are also the good option for supplemental lights in other facility and open-space plant lightings, other artificial lights, such as fluorescent and HID lights, could also be recommended as LEDs are somewhat more expensive compared to those and due to the relatively short illumination time used each day, the advantage of long lifetime for LEDs can not be fully reflected in such applications. Therefore, there might exist such situations when the LED has already been damaged before much of its lifetime is still left.

On the other hand, lighting system would take the highest cost in constructing and running a plant factory. Therefore, careful planning, choosing, arranging, and controlling of the system should be done to significantly reduce the lighting cost, increase lighting efficiencies, and bring about better lighting effects. To achieve these goals, the only way is to conduct sufficient experiments for different plants under various cultivating conditions to acquire the required data for the optimization of the system.

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CHAPTER

2.2

Plant Growth and Physiological Responses to Light Conditions

Naoya Fukuda

Faculty of Life and Environmental Sciences, University of Tsukuba, Tsukuba, Ibaraki Prefecture, Japan

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2.2.1 INTRODUCTION

Light has two major roles in plant growth. The first is as an energy source for photosynthesis. The second is as a signal that, for example, controls plant growth or changes the timing of flowering and affects morphogenetic traits, such as plant height and shape. Plant growth and development are sometimes influenced by changes in the irradiated light spectrum and light quality [1]. For example, the shape of geranium leaves can be modified by light quality, as shown in a previous study [2]. Light signals are received by photoreceptors in plant cells [3]. Plant photomorphogenesis is mediated by the photoreceptors and signal transduction systems in plant cells of tissues such as the shoot tips and young leaves. The

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signals from photoreceptors can regulate the expression of genes concerned with cell division and enlargement, which can form various tissues such as floral buds and leaf primordia. Photoreceptor signals can, thus, induce floral bud formation and change plant shape. For example, shape of the petunia plant can be changed by differences in the ratio of red to far-red light [4, 5]. Moreover, increasing the percentage of far-red light can induce petiole elongation in *Arabidopsis thaliana* [6]. Light signals control floral induction genes via photoreceptor stimulation [3, 7, 8]. When light with a specific quality turns on the "gene switch" associated with floral bud initiation, early blooming is induced.

2.2.2 SIGNAL TRANSDUCTION FROM PHOTORECEPTORS INDUCES FLORAL BUD FORMATION

Cryptochrome (CRY) and phytochrome (PHY) are typical photoreceptors, well-known for controlling floral induction genes such as *FT* (*Flowering Locus T*) and *SOC1* (*Suppression of Overexpression of Constans 1*) and the stability of CO (CONSTANS) protein [3, 7, 8]. A blue light signal from CRY stimulates *FT* and *SOC1* expression via increased CO protein stabilization, which leads to activation of *AP1*; this in turn induces meristematic tissue differentiation and can induce early flowering in *A. thaliana*. In contrast, the red-light signal from PHY B inhibits CO protein stability and can cause late flowering [9]. Far-red light can independently promote *FT* expression in *A. thaliana* [10]. The main light spectra that control flowering timing are blue, red, and far-red [11].

Blue light can be absorbed by CRY, which then emits a signal for floral induction [3]. We have demonstrated changes in the relative expression of *FT* in *A. thaliana* after light treatment [12]. In this experiment, the monochromatic blue light spectrum greatly increased *FT* expression—by about 100 times, 12h after the start of blue irradiation—in wild-type *A. thaliana*. However, mutant *cry2* of *A. thaliana*, which has lost the *CRY 2* gene, did not respond to blue light. Monochromatic blue light stimulated CRY, and its signal acted to switch on floral induction genes such as *FT*. The signal from CRY can inhibit the expression of *COP1* (*Constitutively Photomorphogenic 1*), which depresses CO protein accumulation [13]. The increased level of CO under blue light can, thus, induce early flowering in *A. thaliana*. PHY A, which can absorb far-red light, emits a signal to induce floral bud initiation [10]. These genetic systems for the control of flowering operate mainly through the responses of short-day and long-day plants to changes in photoperiod. Details of the mechanism of flowering control by light in *A. thaliana* have already been reported [9,42].

Previously, we reported that the flowering of petunia (*Petunia* × *hybrida*) was delayed in plants grown under red light and was accelerated in plants grown under blue light [12, 15, 16]. We have already reported that the expression of *FBP28*, a *SOC1-like* gene, is reduced and induced in petunia plants grown under red and blue light conditions, respectively [12]. As described above, some specific light spectra such as blue and far-red light can promote floral bud formation, through photoreceptors PHYA, CRY, FKF1, and UVR8 [17]. However, in the case of tomato, blue light could be a repressor signal for floral bud formation [18]; CRY2 in tomato was overexpressed and inhibited flowering. The effect of the signal from photoreceptors on floral induction depends on the plant species.

2.2.3 PHOTOPERIOD CAN MODIFY PLANT GROWTH AND TIMING OF FLOWERING

Photoperiod is one of the most important environmental factors for inducing floral bud formation. We can also extend day length for photosynthesis by using lighting at night to regulate plant growth. In short-day plants, such as chrysanthemum (*Chrysanthemum* × *morifolium* Ramat.) and beefsteak plants (*Perilla frutescens*), floral bud formation is inhibited by lighting during the middle of the night. In strawberry, providing lighting during the night (night break) is used to inhibit the dormancy of flower buds [19].

In the case of *A. thaliana* grown under long-day (LD) conditions, the expression of *FT* peaks at the end of the day and decreases during the night [20]. This is mainly because the direct inducer of *FT*, CO protein, which is regulated by the clock genes such as *CIRCADIAN CLOCK ASSOCIATED 1* (*CCA1*), *LATE ELONGATED HYPOCOTYL* (*LHY*), and *TIMING OF CAB EXPRESSION 1* (*TOC1*), accumulates by the end of the day and decreases during the night [20]. An *FT* orthologue in rice, *Hd3a*, and *FT* orthologues in *Pharbitis*, *PnFT1* and *PnFT2*, are also expressed in a clock-controlled manner through diurnal changes in the CO protein [21, 22]. The stability of the CO protein is influenced by the signals from photoreceptors. Three kinds of photoreceptors, PHYA, FLAVIN-BINDING, KELCH REPEAT, F-BOX 1 (FKF1), and CRY, maintain the stability of the CO protein [42]. These receptors can absorb some specific spectra, far-red (PHYA) and blue light (FKF1 and CRY), and the signal can promote floral bud induction in *A. thaliana*.

Extended day time can promote plant growth, because the accumulated light energy increases with the extended day time [23]. However, morphogenesis is also a factor that induces a higher growth ratio under extended day length. Spinach is a typical long-day plant and extended day time will induce early flowering. On the other hand, the extended day time sometimes increases the growth ratio of spinach [13]. In the case of spinach, the extended day length induced high levels of gibberellic acid (GA) synthesis in the plant body [24]. Under long-day conditions, the petiole and stem length were extended, and these plant shapes are effective for light perception [13].

2.2.4 PHOTORECEPTORS HAVE MAJOR ROLES IN PLANT GROWTH REGULATION MODIFIED BY PHYTOHORMONES

Many researchers have reported the effects of light quality on the growth of various plant species, including chrysanthemum, petunia, and geranium [2, 25–28]. We have also studied the effects of light quality on petunia growth [2, 4, 5, 12, 15, 16, 29]. In general, most commercial cultivars of petunia grow many lateral shoots and flowers from the short main shoot under usual light conditions, such as solar radiation. However, under blue light conditions, elongation of the main shoot is promoted and early flowering is observed on the main shoot [29]. In contrast, under red light-emitting diodes (LEDs), petunia plants have short main shoots, long and abundant lateral shoots, and late flowering.

In general, changes in plant morphogenesis are induced by phytohormones, and some types of phytohormone are regulated by light quality [30]. In the case of petunia, higher

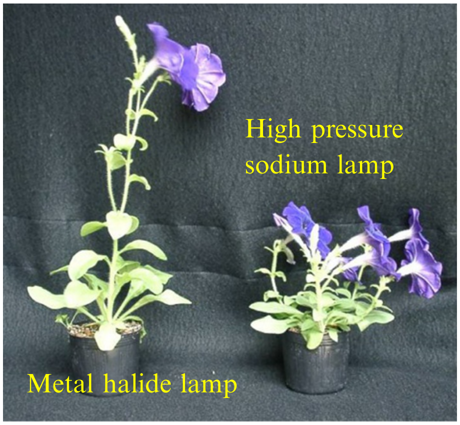

FIG. 2.2.1 Plant shape of petunia under two different artificial lighting, metal halide lamp and high pressure sodium lamp [5].

red (R) and far-red (FR) light ratio (R/FR ratio) conditions (Fig. 2.2.1) [5] during the daytime can be an inhibitor of the biosynthesis of active GA and can induce dwarfism. In the case of sunflower, FR light induced hypocotyl elongation and was associated with an increase in GA biosynthesis [31].

Blue and red light can induce antagonistic responses in plants. In previous studies, petunia plants had elongated main shoots with few lateral branches under blue light conditions [15]. Under blue light conditions, the auxin content was slightly higher than that under red-light conditions [12, 15]. However, the content of active GA varied markedly between red and blue light conditions. On day 14 of treatment with red LEDs, GA_4 was detected in trace amounts, whereas under blue LEDs, the levels were around $10\,\mathrm{pg\,g\,FW^{-1}}$. Under red light without GA application, plants were dwarfed, with an increase in the number of lateral shoots. However, after GA_3 application under red LEDs, plant height increased, and responsiveness to GA in terms of main shoot elongation remained. From those results, we concluded that the change in plant shape under different monochromatic light conditions could be mediated by phytohormones, such as GAs [15]. Under blue LEDs, production of GA 20-oxidase—one of the key enzymes in the synthesis of active GAs—increased in the shoot tips during the daytime [12, 15]. Expression of *PhGA20ox-1S* and *PhGA20ox-2L* (the two genes homologous for encoding GA 20-oxidase in *A. thaliana*) under blue LED treatment was about two to five times that under red LED treatment for 6 h after light treatment. Under blue light, synthesis of active GA was increased [12]. Upon red-light stimulation of PHY signaling in petunia, the transcript levels of the GA 20-oxidase genes were inhibited, resulting in a low content of active GA [12]. In *A. thaliana*, red light also inhibits the GA 20-oxidase gene and induces shortening of petioles [6]. *GASA4* is down- and upregulated by far-red and red light, respectively, in *A. thaliana* [32]; *GASA4* activity decreases GA synthesis.

GA is also an important factor in the control of flowering time. Chen et al. [32] reported that a *gasa4* mutant showed early flowering, and that the phenotype was similar to that of plants under far-red light. The low level of active GA in petunias grown under red light could be an indirect factor in the inhibition of floral bud development. The signal from PHY B stimulated by red light could inhibit the expression of the genes related to active GA biosynthesis. The signal from PHY B also inhibits GA 20-oxidase genes and can reduce the content of active GA and cause dwarfism. However, under blue light, there are no, or few, signals from PHY B; the content of active GA can thus increase and promote floral bud formation.

In addition to phytohormone biosynthesis, the responses of phytohormones can also be changed by light quality. From our studies [15], it appears that plants are less sensitive to GA when red light is present compared to blue light alone, probably due to inhibition of positive GA signaling by red light even in the presence of enhanced GA levels. This may be because red light somehow downregulates the receptor number or inhibits the attraction between the receptor and bioactive GA. Different sensitivity to GA, as a consequence of altered expression of the *GID1* GA receptor, has been demonstrated in *A. thaliana* [33].

2.2.5 CHANGES IN METABOLITES IN THE PLANT BODY UNDER DIFFERENT LIGHT CONDITIONS

The plant body contains various kinds of secondary metabolites. In those secondary metabolites, there are many chemical materials, such as vitamin C, polyphenol, and amino acids, which have functions related to human health care.

It has been shown that light conditions can change the metabolite situation in plant bodies. In the case of lettuce, some light conditions, such as light quality, photoperiod, and light intensity, can increase the antioxidant capacities, content of vitamin C, etc. [14, 34, 35]. In our study, overnight lighting induced higher levels of chlorogenic acid, one of the polyphenolic compounds found in lettuce [36]. Light quality is also a crucial factor in the regulation of metabolite synthesis. The quercetin content and flavonol synthase gene expression in lettuce were increased under UV-B and blue overnight lighting [37].

Pigmentation of fruits and plant bodies is also changed by light quality. In the case of tomato, the redness of the epidermal tissues originates from the carotenoid and lycopene content. The enzyme phytoene synthase is a key mediator of the pathway for synthesis of these pigments. Schofield and Paliyath [38] showed that phytoene synthase activity is regulated by irradiated light qualities and that red light promotes it via the PHY signal. We conclude that not only the content of pigment, but also that of other secondary metabolites such as ascorbic acid and chlorogenic acid are affected by irradiance level and light quality, and that lighting technology could, therefore, be used to control phytochemical content.

2.2.6 CONCLUSIONS

Light conditions, such as light quality and photoperiod, are signals for plant growth and morphogenesis regulation and could become a stimulus for switching on the expression of specific genes through transcription factors. Changes in gene expression modified by signals from photoreceptors can regulate the development and differentiation of plant tissues associated with various phenotypes such as fruit size, fruit skin color, plant shape, and plant metabolites. As described in this chapter, the light signal can change the phytohormone status in a plant body and can induce morphogenetic changes. The signals from photoreceptors can regulate gene expression and the metabolites and phytohormones will have synchronous effects on plant phenotype (Table 2.2.1).

TABLE 2.2.1 Photorecepters, Signal Transductions, Phytohormones, Gene Expressions, and Plant Growth Responses Related to the Specific Spectra [15, 17, 38–41]

Spectra	Photoreceptors	Signal Transduction and Gene Expressions	Plant Growth Responses	Phytohormones and Metabolites Associated With Photoreceptors
UV	UVR8	CHS HY5 COP1	UV-B tolerance Hypocotyl growth inhibition Plant defense responses	
Red and far-red	Phytochrome A B C D E	Phytochrome-interacting factors Circadian clock genes Floral induction genes MYB genes Gibberellic acid biosynthesis Auxin metabolism Ethylene biosynthesis	Germination Etiolation Petiole length Stem elongation (Shade avoidance) Floral induction	Gibberellic acids Auxin Ethylene Carotenoids Chlorophyll
UV-Blue	Cryptochrome 1 and 2	Circadian clock genes Floral induction genes HY5 ABA biosynthesis WRKY ZnF CPRF GBF	Hypocotyl growth inhibition Circadian rhythms Floral bud formation	Gibberellic acids ABA
UV-Blue	Phototropin 1 and 2	Blue light-deoebdebt ser/thr kinase Phospho-signaling pathway	Leaf flattening (Epinasty) Phototropic responses Stomatal opening Chloroplast localization movement	Auxin
UV-Blue	ZTL/FKF1/LKP2	Circadian clock genes Floral induction genes	Circadian rhythms Floral bud formation	

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CHAPTER

2.3

Plant Circadian Rhythms and Vertical Agriculture

Fiona E. Belbin, Donald P. Fraser, Nicholas E. Comben, Antony N. Dodd

School of Biological Sciences, University of Bristol, Bristol, United Kingdom

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2.3.1 CIRCADIAN RHYTHMS IN PLANTS

The daily rotation of the Earth on its axis produces 24 h cycles in environmental conditions. This includes daily cycles in the availability of light for photosynthesis, ambient temperature, relative humidity, and also biotic factors such as herbivore activity. Circadian rhythms are thought to have evolved as an adaptation to these daily changes in the environment [1, 2]. Circadian rhythms are endogenous and self-sustaining biological cycles with a period of about 24 h that persist in the absence of external cues. In plants, circadian rhythms impact a variety of traits of agricultural importance such as photosynthesis and productivity [3], seed production [4], starch accumulation [5], and season of flowering [6]. Given the importance of circadian regulation for plant performance and the intimate relationship between the growth environment and circadian regulation, processes associated with circadian regulation in

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plants have the potential for manipulation in artificial light-type plant factories in order to optimize yield and product quality. Here, we discuss underpinning features of circadian regulation in plants to indicate how an understanding of these mechanisms might be advantageous for vertical agriculture.

2.3.2 GENERATION OF CIRCADIAN RHYTHMS

Circadian systems are generally considered to incorporate several conceptual modules (Fig. 2.3.1). The first of these modules is the circadian oscillator, which generates the 24h circadian rhythm. The second of these is the entrainment pathways, which adjust the phase of the circadian oscillator so that it matches the phase of the environment. The third module comprises the output pathways, which communicate the measure of the time of day that is generated by the circadian oscillator to circadian-regulated processes within the cell. Within plants, each cell is thought to contain a semiautonomous circadian oscillator, with some weak intercellular coupling between cells of the rhythms [7, 8].

Most information about the architecture of the plant circadian oscillator is derived from research using the experimental model *Arabidopsis thaliana*. The Arabidopsis circadian oscillator is thought to comprise at least three interconnected transcription-translation feedback loops [1]. One loop includes the MYB-like transcription factors CIRCADIAN CLOCK ASSOCIATED1 (CCA1) and LATE ELONGATED HYPOCOTYL (LHY) forming a regulatory interaction with TIMING OF CAB2 EXPRESSION 1 (TOC1). Transcripts encoding *CCA1* and *LHY* peak in the morning and their protein products repress the transcription of *TOC1* by binding to its promoter [9, 10]. Toward the end of the day, CCA1 and LHY protein abundance decreases, allowing TOC1 to accumulate and repress transcription of morning-expressed transcripts such as *CCA1* and *LHY* [10–12]. A protein complex known as the evening complex, incorporating LUX ARRHYTHMO, EARLY FLOWERING3 (ELF3), and ELF4, downregulates *TOC1* transcription which in turn allows transcription of *CCA1* and *LHY* in the morning [13–15].

Another loop within the circadian system contains PSEUDO-RESPONSE REGULATOR5 (PRR5), PRR7, and PRR9, which also bind to the promoters of *CCA1* and *LHY* and repress their activity [16]. CCA1 and LHY can activate the transcription of *PRR* genes, explaining why the *PRR* transcripts peak several hours after the early morning genes [17]. There is a

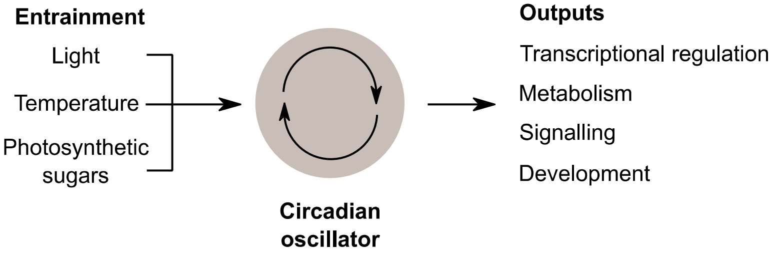

FIG. 2.3.1 Generalized structure of circadian systems. The circadian oscillator is entrained by input signals that adjust the circadian phase to match the phase of the environment. The circadian oscillator produces an estimate of the time of day that is communicated to multiple aspects of physiology, metabolism, and development through rhythmic regulation of gene transcription.

sequential pattern of *PRR* gene transcript accumulation, starting with *PRR9* 2–3h after dawn and ending with *TOC1* accumulation (identified also as *PRR1*) in the evening [18]. Other regulatory mechanisms within the circadian system include CCA1 and LHY directly suppressing the transcription of *EARLY FLOWERING4* (*ELF4*) and *LUX ARRHYTHMO* (*LUX*) [19], ELF3 and ELF4 repressing transcription of *PRR7* and *PRR9*, and finally LUX repressing *PRR9* transcription [14]. It has also been suggested that CCA1 and LHY can negatively autoregulate their own and each other's transcripts and that LHY can repress all other oscillator components [10].

In addition to transcriptional feedback loops, posttranscriptional mechanisms such as RNA splicing and the control of RNA and protein stability contribute to the functioning of the circadian oscillator [20, 21]. Furthermore, there are other components of the clock not described here and probably more yet to be identified.

2.3.3 INTERACTION BETWEEN CIRCADIAN REGULATION AND LIGHT SIGNALING

Light is the main entraining stimulus for the plant circadian oscillator and provides plants with information about the local environment. By manipulating the light quality, light intensity, and the timing of light delivery, we suggest that growers might be able to capitalize upon the involvement of circadian regulation in plant physiology and development to increase yield and product quality. In this section, we discuss some interactions between circadian regulation and light signaling to highlight candidate mechanisms for the manipulation of crop performance.

Phytochrome and cryptochrome photoreceptors contribute to circadian entrainment in response to red and blue light [22]. Under increasing light intensity (fluence rate), cryptochromes mediate a progressive shortening of the circadian period [22]. Phytochrome A (phyA) mediates low fluence red light signaling to the circadian oscillator and appears to participate in low fluence blue light entrainment [22]. Studies on the *phyABCDE* quintuple mutant found that at low fluence rates ($<10\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$), *phyABCDE* had a shorter circadian period than wild type [23]. This might be because the Pfr form of phytochrome accelerates the pace of the circadian oscillator, whereas the Pr form of phytochrome decreases the pace of the circadian oscillator [23]. In addition to photoreceptor-mediated signals, sugars produced by photosynthesis entrain the circadian oscillator through a mechanism involving the circadian oscillator component PRR7 [24].

The mechanisms that communicate light information from the photoreceptors to the circadian oscillator are less well-defined. Under conditions of continuous far- red light, there are substantial changes in the functioning of the circadian oscillator. Continuous far-red light suppresses the morning-phased promoter of *CCA1* and upregulates the evening-phased promoters of *TOC1*, *GI*, and *CCR2*, accompanied by a general damping of rhythmic transcript accumulation [25]. ELF4 appears to mediate far-red light inputs to the circadian oscillator, and the positive phyA signaling partners FHY3, FAR1, and HY5 directly activate ELF4 [19], but this mechanism does not underlie entrainment [25]. Far-red light input to the circadian system also involves the MYB-like transcription factor REVEILLE8 (RVE8) [26]. RVE8 binds to evening element-containing promoters to activate their expression, and RVE8 expression is promoted by phyA in response to far-red light [27].

The UV-B photoreceptor ULTRAVIOLET RESISTANCE LOCUS8 (UVR8) [28] can influence the pace of the circadian oscillator. Both high fluence UV-B and UV-B pulses shift the circadian phase [29]. While circadian entrainment by UV-B involves UVR8 and CONSTITUTIVELY PHOTOMORPHOGENIC1 (COP1), it does not require ELONGATED HYPOCOTYL5 (HY5) and HY5-HOMOLOG (HYH). This differs from most UVR8-mediated responses, which involve HY5 and HYH [29].

Light also influences the circadian oscillator through posttranslational mechanisms. ZEITLUPE (ZTL) is a LOV domain blue-light-sensitive protein that alongside its homologs FLAVIN BINDING KELCH REPEAT, F-BOX (FKF1), and LOV KELCH PROTEIN 2 (LKP2) ubiquitinates TOC1 and PRR5 and targets them for proteasomal degradation [30]. Blue light promotes an interaction between ZTL and GIGANTEA (GI), which stabilizes these proteins and increases circadian amplitude, presumably through the interaction between ZTL and TOC1 that regulates TOC1 degradation [31].

There is a complex interaction between circadian regulation, photoperiod length, and responses to light quality. One mechanism regulating these interactions involves the PHYTOCHROME-INTERACTING FACTORS (PIF) family of bHLH transcription factors. The PIFs control a range of growth-promoting genes involved in mechanisms such as auxin synthesis, auxin transport, and cell wall loosening [32]. There is circadian regulation of PIF transcript and protein accumulation [15], providing a connection between circadian regulation and light signaling. PIF activity is also regulated posttranscriptionally by interaction with the PSEUDO-RESPONSE REGULATORS (PRRs) of the circadian oscillator, forming complexes with curtailed transcriptional activity [33–35]. The regulation of PIFs by both the circadian oscillator and photoreceptors underlies a change in hypocotyl elongation that occurs under differing photoperiods, providing a connection between photoperiod, the circadian oscillator, and development [36].

One reason why so many photoreceptors provide light inputs to the circadian oscillator might be to entrain the oscillator accurately within the range of light conditions present in the environment [22]. This also provides a toolset that can be exploited by growers to tune the architecture and metabolism of plants, by both altering the functioning of the circadian oscillator and through direct effects of photoreceptors upon development and physiology. For example, the architecture of cultivated coriander plants can be manipulated by controlling the UV-B light environment [37]. Given the relative ease with which the entire light spectrum can be controlled within an artificial light-type plant factory, understanding the relationship between photoreceptors, signaling, development, and the circadian oscillator in crops provides scope to control crop performance within plant factories.

2.3.4 COUPLING OF THE CIRCADIAN OSCILLATOR TO CIRCADIAN-REGULATED PROCESSES

A core mechanism by which the circadian oscillator regulates cellular processes is through the control of transcription. Within Arabidopsis, a substantial proportion of the transcriptome (6%–31%, depending on experimental and analysis strategy) is subject to circadian regulation

[38–40]. This appears to occur through circadian-regulated promoter motifs, with specific promoter motifs being associated with specific circadian phases of transcriptional regulation [38, 39]. For example, CCA1/LHY repress *TOC1* transcription by binding to the evening element motif within its promoter [9]. Components of the circadian oscillator directly regulate sets of genes; for example, TOC1 binds to 867 genomic loci, with 40% of these genes being circadian-regulated [12], and CCA1 binds to 449 genomic loci [41]. In addition to direct transcriptional regulation, posttranslational processes such as Ca^{2+} signaling, poly ADP ribosylation, and sumoylation might participate in circadian regulation of cellular processes [42–44].

The circadian oscillator can also restrict responses to environmental stimuli to certain times of day [45]. This process is known as "circadian gating" and has particularly widespread effects upon the responses of plants to light. For example, under constant light conditions, the *CAB2* promoter is not responsive to light pulses during the entrained night (subjective night), but is activated by light during the subjective day [46]. The circadian oscillator also gates the accumulation of *HYH* and *CHALCONE SYNTHASE* transcripts in response to UV-B, such that the induction of these transcripts by UV-B is restricted to the subjective morning [29]. There is circadian gating of the shade avoidance response of plants, which is a developmental process caused by light conditions incorporating a low red to far-red ratio [33, 47]. A transcriptional response to low red/far-red light of the TOC1-interacting protein PIL1 is gated by the circadian oscillator, with *PIL1* induced strongly by low red/far-red at subjective dawn, but less so at subjective dusk [47]. Seedling hypocotyls also elongate more in response to a low red/far-red light pulse at subjective dusk compared with their response to a low red/far-red light pulse at subjective dawn [47]. Circadian gating is not restricted to just light signaling. For example, the cold-induced transcript *CBF1* is induced by varying magnitudes depending on the time of the cold treatment, with maximum sensitivity of *CBF1* to cold occurring 4 hours after subjective dawn [48]. The mechanisms underlying circadian gating are not fully understood and could involve chromatin remodelling [49]. An important implication of circadian gating is that the responses to environmental manipulations of plants within vertical agriculture systems will be influenced by the time of day of the environmental manipulation.

2.3.5 CIRCADIAN REGULATION OF PHYSIOLOGY AND METABOLISM WITHIN THE CONTEXT OF VERTICAL AGRICULTURE

The circadian oscillator regulates a range of processes of agricultural and horticultural importance. Arabidopsis circadian oscillator mutants that are arrhythmic or have altered circadian periods grow more slowly than wild-type plants [3]. Furthermore, when the endogenous circadian period differs from the daily period of the environment, growth rates are reduced in Arabidopsis, tomato, and peas [3, 50]. One potential explanation for these phenotypes relates to the role of circadian regulation in the accumulation and utilization of transitory starch [5], because the circadian oscillator contributes to the timing of nocturnal starch utilization to ensure that transitory starch supplies are not exhausted before dawn. Many cultivated tomato varieties have a long circadian period (up to 28 h), which is thought to be a consequence of breeding tomatoes for cultivation in higher latitudes with longer summer photoperiods due to the high level of sensitivity of tomato to inappropriately timed light [50–52]. This suggests that the relationship between endogenous rhythms and periodic light environment represents an important consideration for artificial light-type plant factories, within which the periodic light environment is flexible and can be tuned to alter plant performance. One success in this area is the finding that the screening and analysis of circadian rhythms in lettuce seedlings within a plant factory allows selection of those seedlings that will produce consistently performing plants [53].

The circadian oscillator also controls the opening and closing of stomata by the stomatal guard cells. Under continuous light conditions, stomatal conductance to water vapor is greater during the subjective day than subjective night [54], and this daily rhythm of stomatal opening is altered in circadian oscillator mutants. For example, the short period *toc1*-1 mutant and long period *ztl*-1 mutant cause short and long circadian periods of stomatal opening, respectively [55, 56]. Under light/dark cycles, overexpression of the circadian oscillator component CCA1 leads to greater transpiration during the light period [3]. This potentially reduces the water use efficiency (the ratio of carbon uptake by photosynthesis to water lost by transpiration), especially because the rate of photosynthesis is also reduced in CCA1-ox under light/dark cycles [3].

Stomatal aperture is also regulated by an interaction between the circadian oscillator and ABA signaling. TOC1 overexpressors have decreased sensitivity to ABA and the *toc1*-2 mutant is ABA-hypersensitive, which may be due to interaction between TOC1 and the promoter of the gene encoding the H subunit of Mg^{2+}-chelatase (*H SUBUNIT OF MG-CHELATASE / GENOMES UNCOUPLED5 / ABAR*), which participates in ABA signaling [57]. This might explain why a *TOC1* knockdown line loses less water and is more drought-tolerant than the wild type [57]. Overexpression of CCA1 exclusively within Arabidopsis guard cells increases biomass under well-watered conditions, and these guard cell-specific CCA1 overexpressors are also slightly more sensitive than the wild-type to mild drought [58]. These studies indicate that the circadian oscillator influences the water requirements of plants and potentially their water use efficiency. This suggests that establishment of environmental conditions that elicit certain circadian properties, or identification of genotypes with specific circadian traits, might represent tools to reduce horticultural water requirements within vertical agriculture systems. This might be of particular value for aeroponic-type cultivation systems.

Secondary metabolites confer flavors to edible plants, and there is circadian regulation of genes associated with the synthesis of these metabolites. This includes rhythms in the abundance of transcripts encoding enzymes associated with phenylpropanoid metabolism and glucosinolate metabolism [38, 59]. Interestingly, changes in the expression of a gene associated with glucosinolate metabolism (*AOP2*) can alter the daily timing of transcription of sets of genes [59]. This could suggest that environmental, nutritional, or genetic manipulations to adjust glucosinolate composition of plants cultivated within vertical agriculture systems might produce unforeseen alterations in circadian rhythms of gene expression, altering growth rates or flowering time.

In Arabidopsis, several transcripts associated with terpene synthesis are also circadian-regulated. This includes *TERPENE SYNTHASE3* (*TPS3*), *TPS30*, *PUTATIVE PENTACYCLIC TRITERPENE SYNTHASE3*, and *BAUROL SYNTHASE1*, along with circadian regulation of transcripts encoding several enzymes within the mevalonic acid pathway (*HYDROXY METHYLGLUTARYL COA REDUCTASE1* (*HMG1*), *HMG2* and *At1g31910*) [60]. This raises the possibility that manipulation by growers of the circadian oscillator could be exploited to alter the accumulation of flavor-conferring terpenes. Furthermore, the environmental consistency within plant factories means that the timing of harvest is independent of weather conditions, so crops can be harvested at the optimum time of accumulation of commercially desired metabolites.

2.3.6 CONCLUSIONS

Circadian regulation has a pervasive effect upon plants, regulating their development, primary and secondary metabolism, and responses to environmental stimuli. Given the close relationship between circadian regulation and plant performance, combined with the scope provided by plant factories for the manipulation of circadian oscillator function through environmental stimuli, there is considerable potential within vertical agriculture to exploit the circadian oscillator to enhance productivity and product quality (Fig. 2.3.2). A current constraint is that detailed knowledge of circadian oscillator function is derived from research involving Arabidopsis. This underpinning information will need scaling to plant factory-cultivated species such as tomato and lettuce [53, 61, 62] in order to translate knowledge of circadian regulation derived from model system research into the context of vertical agriculture.

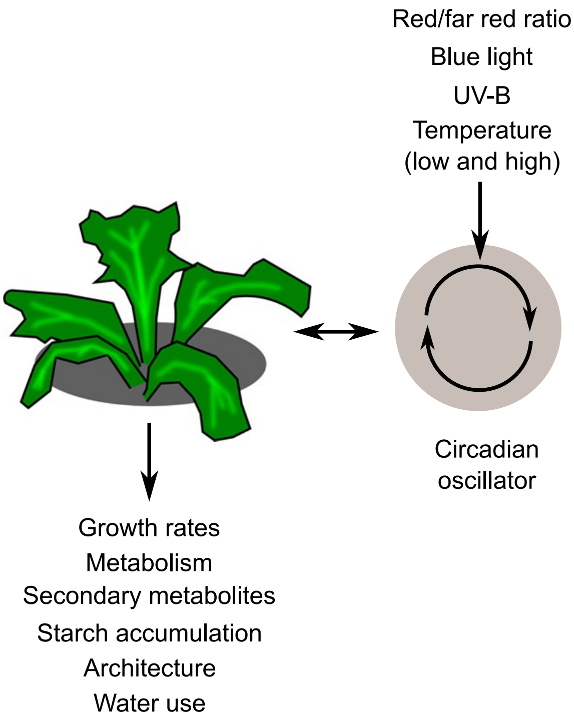

FIG. 2.3.2 Environmental inputs represent candidates for manipulation of circadian function within plant factories. Aspects of plant performance such as growth rates, metabolite accumulation, and water use are regulated by the circadian oscillator, which in turn can be manipulated through alterations in the light and temperature environment.

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CHAPTER

2.4

Control Theory in the Metabolic Rhythms of Plants

Yusuke Tanigaki, Hirokazu Fukuda

Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, Osaka, Japan

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2.4.1 PLANT CIRCADIAN RHYTHMS

The circadian rhythm is universal in biological systems and controls numerous physiological phenomena during the 24-h diurnal cycle. The circadian rhythm is constituted by autonomous oscillation of expression of clock genes, which in the model plant *Arabidopsis thaliana* include Circadian clock-associated 1/Late elongated hypocotyl (*CCA1/LHY*), Timing of chlorophyll a/b-binding protein (CAB) expression 1 (*TOC1*), and Pseudo-response regulators 5, 7, and 9 (*PRR5, PRR7,* and *PRR9*) [1]. *CCA1/LHY* and *TOC1* form a negative feedback loop and form the central system of the circadian rhythms. *CCA1* functions primarily during the daytime. In contrast, *TOC1* functions primarily at night. Both periodically control downstream genes. Furthermore, clock genes such as *PRRs* mutually control genes, forming a complicated periodic expression system. This system regulates various physiological phenomena such as metabolism, respiration and photosynthesis, flowering, and hormone balance.

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The oscillation of diurnal gene expression results from both environmental cycles and regulation by the circadian clock. Regulation by circadian rhythms ensures the stability of physiologic processes and enables adaptation to diurnal environmental cycles. In fact, the circadian rhythms of plants synchronize with the cycle of the external environment and fluctuate in phase [2]. Fig. 2.4.1 shows the expression pattern of clock gene *CCA1* under different photoperiods in *A. thaliana*. The measurement was of bioluminescence of a recombinant plant into which a gene encoding a fluorescent protein (luciferase) was ligated to the *CCA1* promoter. In continuous light (LL), *A. thaliana* showed autonomous gene expression for 23.5 h. On the other hand, under LD20 (10-h light and 10-h dark)

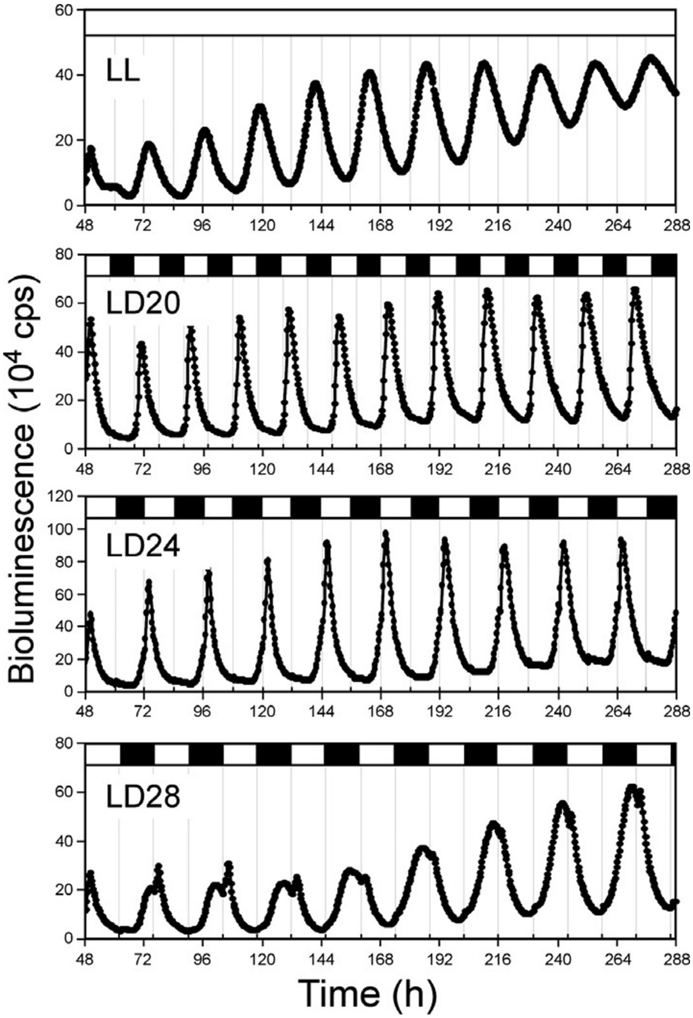

FIG. 2.4.1 Rhythmic expression of clock gene *CCA1* synchronized with light/dark cycles [2]. LL indicates continuous light. LD20 indicates 10-h light/10-h dark conditions. LL24 indicates 12-h light/12-h dark conditions. LD28 indicates 14-h light and 14-h dark conditions. White and black boxes, respectively, indicate the blocks of time with and without light.

and LD28 (14-h light and 14-h dark) conditions, *A. thaliana* became synchronized with each light/dark cycle and showed cycles of gene expression different from those under LL conditions. The circadian rhythm is strongly synchronized with the external environment, but this synchronization interferes with growth if it deviates from the inherent circadian rhythm of the plant (the cycle of *A. thaliana* is ca. 24 h). In contrast, growth is strongly promoted when the periods of the external environment and the circadian rhythm are identical. This phenomenon is called "circadian resonance" [3]. Fig. 2.4.2 shows the results of observation of circadian resonance in *A. thaliana*. Under LD20 and LD28, growth was strongly suppressed, but under LD24, it was the highest observed in any light/dark cycle. On the other hand, growth was maximum under LL conditions. It is thought that growth depends on the amount of photosynthesis per day. However, LL conditions are extremely costly in plant factories using artificial light. Considering the cost, the growth efficiency under LD24 is higher than that under LL.

Research using gene expression analysis has advanced mainly in *A. thaliana*. In recent years, various crops have also been studied. Fig. 2.4.3 shows the difference in the free-running period of the circadian rhythm due to light quality in lettuce (*Lactuca sativa* L.) and the change in yield due to photoperiod [4]. Lettuce is cultivated in many plant factories as a main crop. Lettuce depends on the difference in light quality, which changes the free-running period (Fig. 2.4.3, red LED). Lettuce shows a short free-running period under red light, and the free-running period tends to become longer when blue light is added. These tendencies differ depending on the lettuce variety, and in the cultivar Greenwave, the free-running period due to the difference in light quality does not change. Although various effects of light quality on plant growth are known, its effects on the free-running period are not. Circadian resonance has been reported only for *A. thaliana*, but we have observed the same phenomenon in lettuce (Fig. 2.4.3B) [5]. Greenwave lettuce has maximum fresh weight in LD24 regardless of light quality, but the fresh weight under nonoptimal conditions varies depending on the light quality and is minimum under fluorescent lamps (Fig. 2.4.3B). Because light quality and the light cycle have a large influence on the fresh weight, it is important to determine the optimal light environment to improve cultivation efficiency.

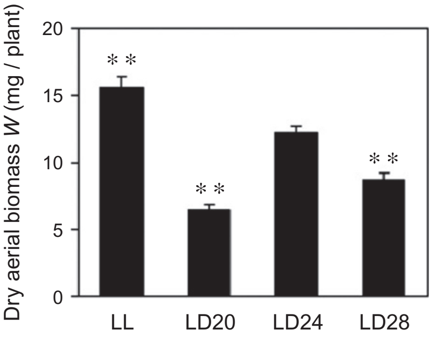

FIG. 2.4.2 Circadian resonance [2]. Double asterisk (**) indicates significance at $P = .01$ (Student's *t*-test).

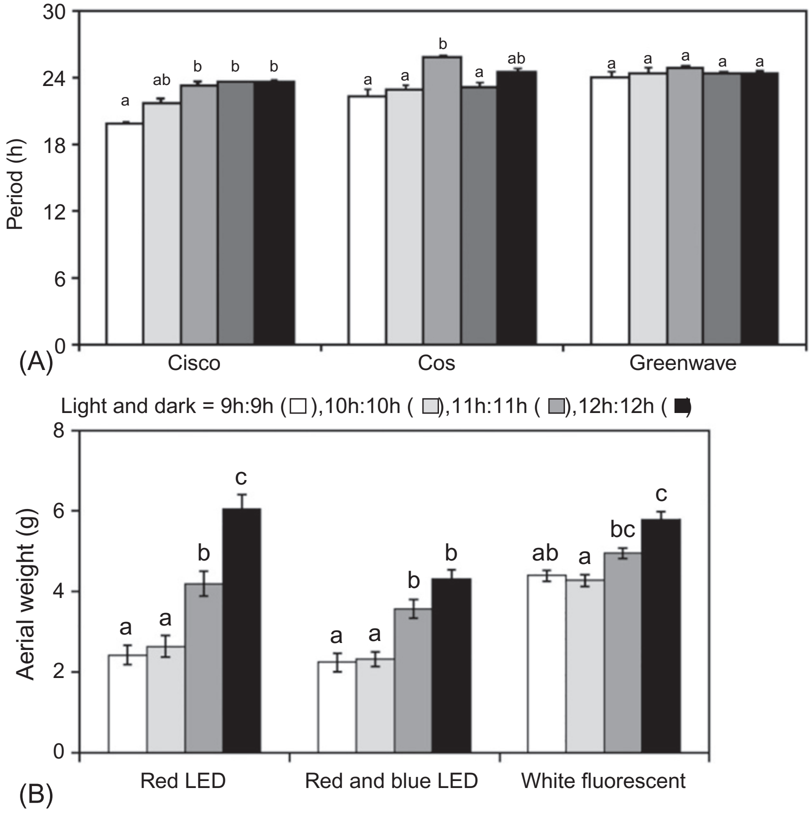

FIG. 2.4.3 (A) Difference in circadian rhythm due to light quality in lettuce and change in fresh weight due to photoperiod [4,5]. Cisco, Cos, and Greenwave are lettuce cultivars. (B) Aerial weight of Greenwave under four period length of light/dark cycles ($P = .05$, Tukey-Kramer test).

2.4.2 DETECTION OF CIRCADIAN RHYTHMS USING MOLECULAR TIMETABLE METHOD

The quality of vegetables depends on plant metabolism, which is controlled by gene expression. The oscillation of diurnal gene expression results from both environmental cycles and regulation by the circadian clock. Regulation by the circadian clock ensures the stability of physiological processes and enables adaptation to diurnal environmental cycles. Thus, it is important to measure circadian rhythms when assessing environmental regulation of vegetable quality.

Of the several methods available to measure circadian rhythm, transcriptome analysis is a particularly accurate approach. Transcriptome analysis involves global capture and is a widely used method regardless of species [6–8]. In transcriptome analysis, RNA is extracted from the tissue and the RNA sequences are determined using a sequencer (e.g., by next-generation sequencing). The determined sequences are then mapped to a reference sequence like that of a genome. The level of expression is inferred based on the number of sequences mapped. Therefore, by obtaining data continuously, periodicity analysis of gene expression becomes possible [9].

In predicting aspects of the phenome such as growth and nutritional quality using transcriptome analysis, gene annotation (genetic information) is very important. Analysis of tomato (*Solanum lycopersicum*), *A. thaliana*, or both can be conducted readily. Figs. 2.4.4 and 2.4.5 are examples of transcriptome analysis of tomato in a sunlight-type plant factory with sampling every 2h [10]; although the environment changed drastically on the third day, gene expression showed stable periodicity. In addition, based on analysis of the transcriptome data, we clarified that plant hormone pathways behave periodically, as if under circadian rhythm control. This physiological information will help to improve yield.

The molecular timetable method is a well-known method for measuring diurnal oscillations based on collective gene expression [11,12]. "Time-indicating genes" are selected from the analysis of the pattern of expression of each gene and fitted with a cosine curve. The peak of this cosine curve, the molecular peak time, indicates the internal time, or body time, of the target plant of analysis. In data from transcriptome analysis of the tomato plants in the sunlight-type plant factory, the selected time-indicating genes showed the same internal time as the external time (sampling time; Fig. 2.4.6) [12]. Hence, the plant circadian rhythm shows stable behavior even in drastically fluctuating environments.

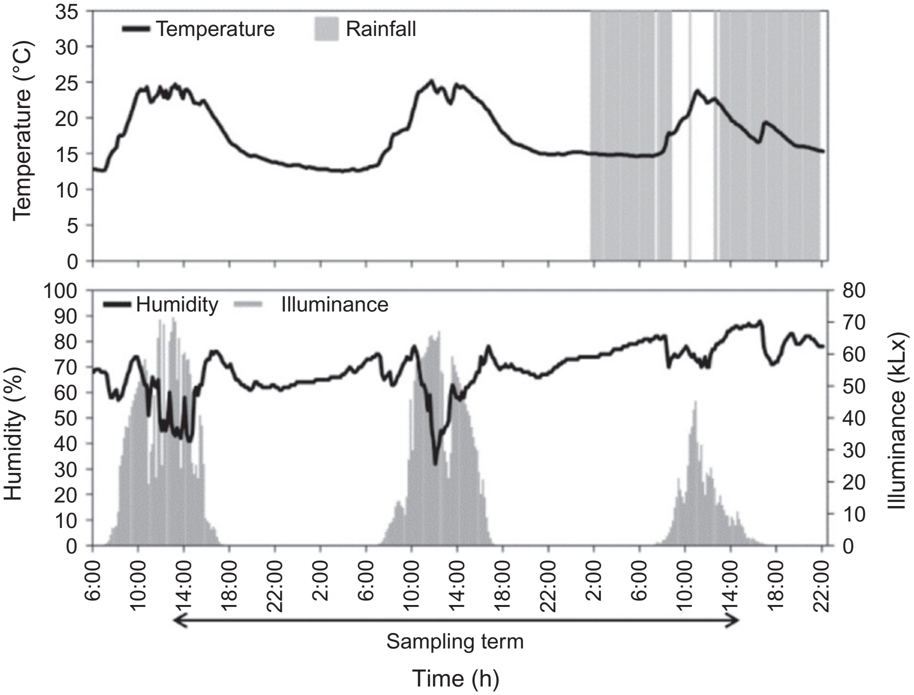

FIG. 2.4.4 Weather at time of sampling in sunlight-type plant factory [10].

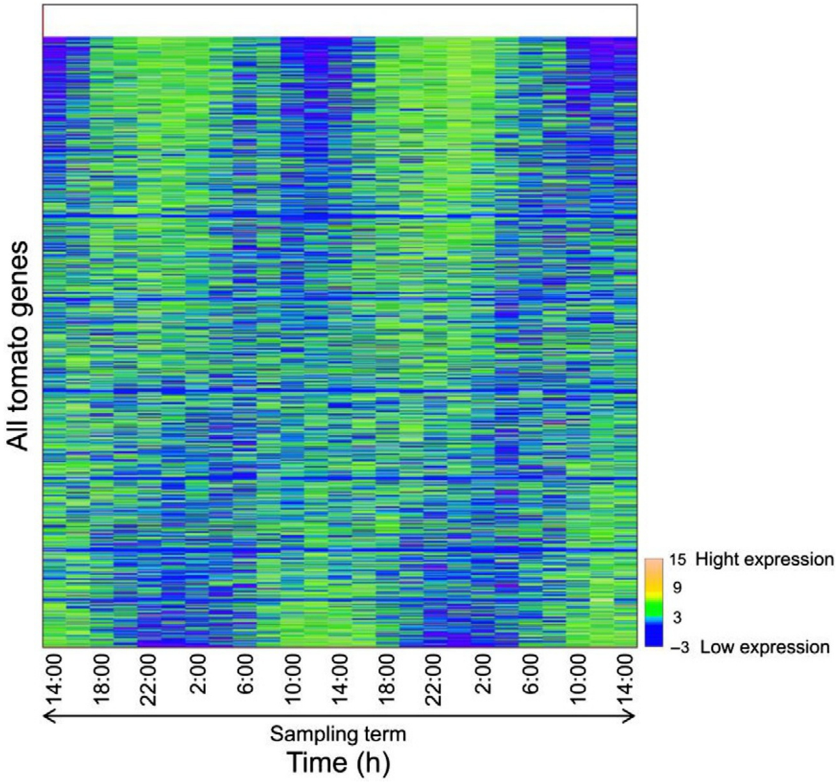

FIG. 2.4.5 Time series analysis of tomato genome [10].

2.4.3 SYNCHRONOUS CONTROL OF CIRCADIAN RHYTHM

The circadian rhythm responds to environmental factors such as light and temperature and can be synchronized with day/night cycles. It is theoretically possible to control synchronization by clarifying the response characteristics to each environmental factor. Fig. 2.4.7 shows that the circadian rhythm in lettuce can be synchronized to a light cycle with small amplitude [4]. The circadian rhythm is synchronized even when blue LED light is cyclically fluctuated at low amplitude (20% fluctuation) in a situation where irradiation with red LED light is constant. As the light cycle changes, Cisco and Cos lettuce synchronize to that light cycle, but Greenwave cannot synchronize to a long-period cycle. Although the mode of synchronization varies depending on the variety, it is possible to control the circadian rhythm by controlling the external environment, especially the lighting. These results show the wide range of circadian rhythm control in a plant factory using artificial light and show the possibility of creating a novel cultivation method by altering the lighting.

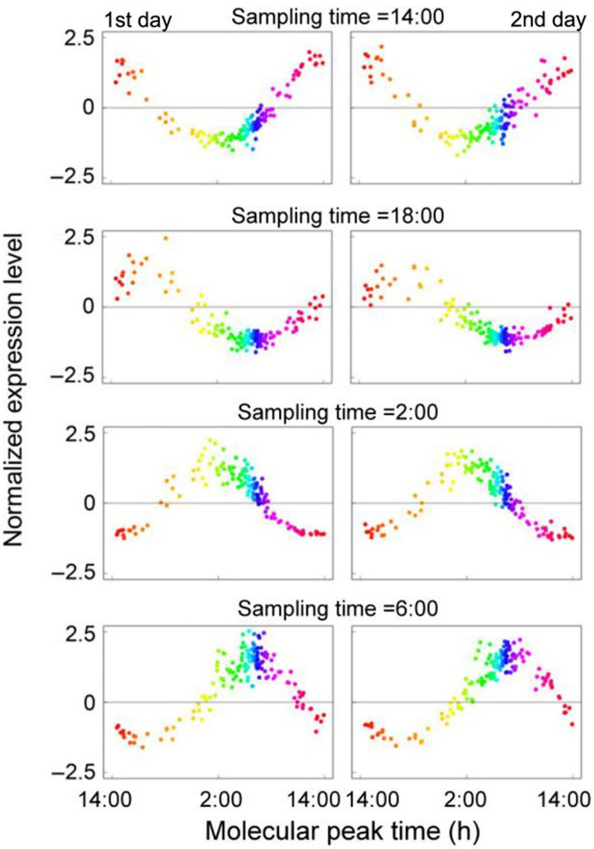

FIG. 2.4.6 Measurement of internal time by molecular timetable method [12].

2.4.4 MATHEMATICAL MODEL OF CELL POPULATION AND REGULATION

In recent years, it has been clarified that almost all cells constituting plants have an autonomous circadian rhythm. In other words, the plant itself is composed of a large number of self-sustained cellular oscillators that synchronize with each other to produce a strong output rhythm, and complicated spatiotemporal dynamics of these cellular oscillators can occur [13–15]. Therefore, in order to precisely control the biological clock of a plant, it is necessary to first construct a mathematical model of a cellular oscillator system consisting of a multitude of cell clocks.

Here, as an example, clock control by pulse perturbation is considered. Fig. 2.4.8A shows the response of the circadian rhythm when 2-h dark pulses under constant light were applied as a pulse perturbation [16,17]. This dark pulse caused a phase shift and change in amplitude.

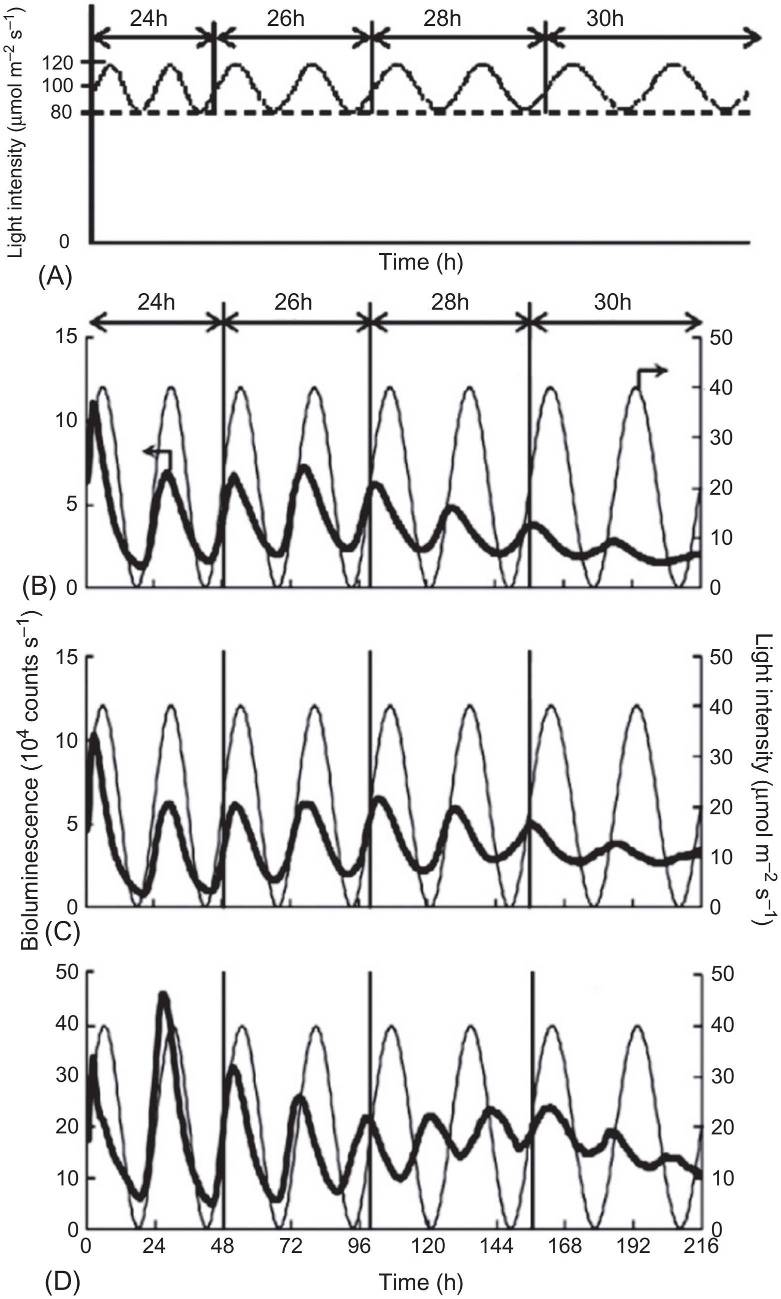

FIG. 2.4.7 Light synchronization of circadian rhythm in lettuce [4] (A) Schematic diagram of light cycle. (B) Cisco (C) Cos (D) Greenwave. (B–D) Thick line indicates bioluminescence (driven by *AtCCA1::LUC* construct) and thin line indicates light intensity.

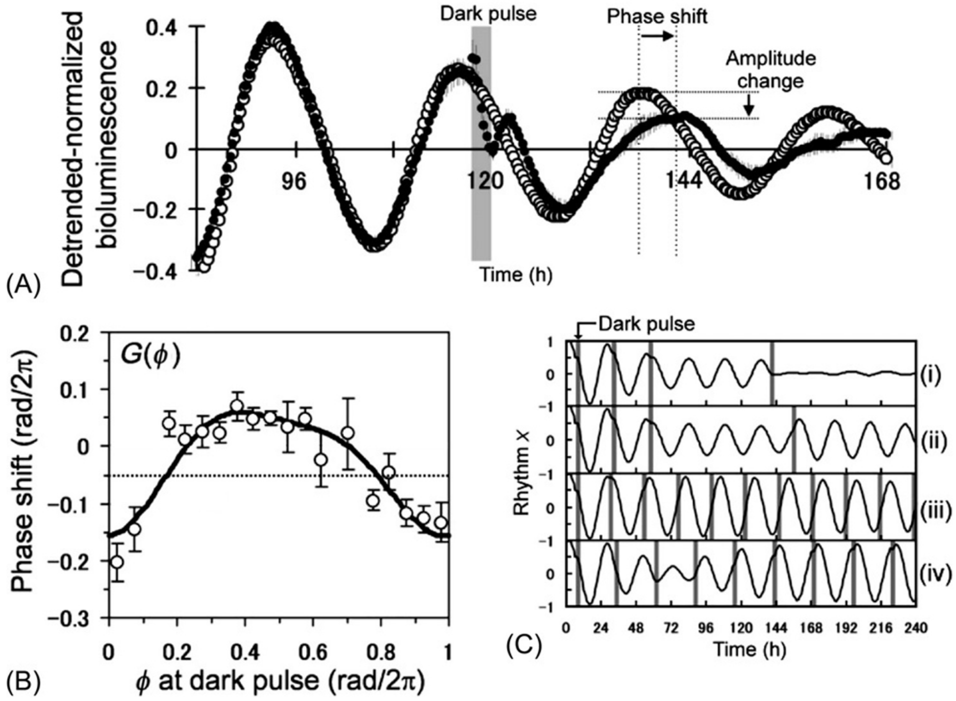

FIG. 2.4.8 Synchronization of cell population by a dark pulse [16]. (A) Circadian rhythm response; *black* and *white circles*, respectively, indicate dark pulse treatment and no treatment. (B) Phase response curve for the dark pulse. (C) Simulation of circadian rhythm at the level of an individual plant; X indicates the rhythm. Vertical lines indicate timing of application of dark pulse.

Fig. 2.4.8B shows the phase response curve (PRC) for the dark pulse, indicating the phase shift of the plant circadian rhythm against phase ϕ, at which the dark pulse was applied. Fig. 2.4.8C shows the results of simulating the influence of multiple dark pulses on the mean oscillation amplitude X in globally coupled phase oscillators based on a model of coupled phase oscillators.

Our control technique is designed based upon the following model of coupled phase oscillators:

$$\frac{d\phi_k}{dt} = \omega_k + [1 - L(t)]Z(\phi_k) + \frac{K}{N}\sum_{j=1}^{N} \sin\left(\phi_j - \phi_k\right)$$

Here, ϕ_k and ω_k are the phase and natural frequency, respectively, of the k oscillator, K represents the coupling strength [16], N is the number of oscillators, and $L(t)$ stands for light intensity ($L(t)=0$ for dark pulse; $L(t)=1$ for light on). The phase sensitivity function $Z(\phi_k)$ for the dark pulse is given by Fig. 2.4.8B. Based on the numerical simulation in Fig. 2.4.8C, the synchronized state was weakened step by step (showing singularity behavior) by a strong desynchronizing effect (1), the synchrony was recovered when the fourth dark pulse was applied at $\phi = 0.85$ rad$/2\pi$ of the sixth cycle (2), and the phase was locked to a stable fixed point, at which synchronized dynamics of the cells were enhanced due to the entrainment and the mean oscillation was amplified upon periodic applications of the dark pulse with either a short cycle or a long cycle (3 and 4, respectively).

For control of the circadian rhythm, it is important to obtain a response function for individual control factors such as an optical pulse. In recent years, mathematical studies on the phase response of circadian rhythms have advanced rapidly [18–20], and it is expected that in the near future, more advanced biological clock control technology will be created.

2.4.5 CONCLUSION

The circadian rhythm is closely related to the external environment. This relationship greatly involves the growth and metabolisms of plants. On the other hand, the circadian rhythm behaves stably against environmental fluctuations. Therefore, control of the circadian rhythm in plant cultivation requires ingenious techniques. In this section, we show that circadian rhythm can be controlled with a simple light control based on a mathematical model of coupled phase oscillators. Our measurement and control technology of the circadian rhythm enables efficient plant cultivation and is a responsible technology for next-generation agriculture.

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CHAPTER

2.5

Nitrate Content Control in Green Vegetables Grown Under LED Lighting

Celine C.S. Nicole, M.P.C.M. Krijn, Udo van Slooten

Philips Lighting Research, Eindhoven, Netherlands

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2.5.1 INTRODUCTION

In greenhouse horticulture, LED lighting has matured to become more and more the only supplemental lighting and is about to replace other types of lighting [1–3]. In more modern

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horticulture, like plant factories [4,5] (also known as vertical farms), LED lighting has been adopted as the source of light because of its high energy efficiency. Plant growth and development under LED lighting is, however, strongly dependent on the environment (climate, CO_2) and growth system (substrate, irrigation method). Because of the well-controlled environment, it becomes possible to also control and predict the nutrient content of horticultural crops grown. Often, leafy green vegetables such as lettuces or baby leaves are chosen to be grown in plant factories. Leafy vegetables are known to accumulate an excessive amount of nitrate [6] and this constitutes a strong health concern in Europe [7]. By adoption of good agricultural practices, it is possible to reduce the nitrate accumulation [8]. However, under low light intensity and with unfavorable climate and irrigation conditions (excessive rain), the nitrate can still accumulate in the plant just before it is harvested. In Europe, the present legislation limits the nitrate in lettuce and spinach when cultivated indoor to 3500 $\mathrm{mg\,kg^{-1}}$ during summer time, while during winter time the limit is higher. In previous work [9], we have shown results concerning limiting the nitrate level of lettuce grown in closed environments while keeping a high yield ($\mathrm{g\,mol^{-1}}$). The low nitrate values measured were rather encouraging for lettuces grown in the absence of sunlight. It is, however, questionable if a much lower nitrate level can be achieved and whether this can be achieved for many different plant species and by adapting the light recipe only. We have chosen to look at the nitrate content of baby leaf spinach and arugula (rocket, rucola). Both crops are produced as young leaves for the fresh produce market. Baby leaf spinach is an important crop with high nutritional value. It is an excellent source of minerals, vitamin K, A, and folic acid. However, spinach is also known to accumulate nitrate and oxalates. For arugula, two species are of importance, these are the “salad” or “cultivated” rucola (*Eruca sativa*) and the “wild” rucola (*Diplotaxis tenuifolia*). Rucola species are known for their high levels of potentially beneficial glucosinolates, flavonols, and antioxidants [10]. An interesting characteristic of rucola cultivation is the ability to regrow their leaves multiple times after harvesting. Some growers harvest up to seven times during one cultivation cycle. This is particularly interesting for plant factories because, between each harvest, we do not have to include a germination step. Even more than spinach, arugula is a crop known for its very high nitrate content (especially the wild type has higher levels than the cultivated type). The European Food Safety Authority (EFSA [7]) found nitrate content in arugula to range in between 4800 and 6400 $\mathrm{mg\,kg^{-1}}$ assayed in various cultivation systems, seasons, and regions in Europe [11]. Consequently, arugula has its own regulation limits in Europe set to 6000 $\mathrm{mg\,kg^{-1}}$ during summer time and 7000 $\mathrm{mg\,kg^{-1}}$ in winter time [12].

Nitrate in leafy green vegetables has been identified for years as posing a health concern. However, recent research also has shown strong benefits of highly concentrated nitrate in green vegetables. This finds an application in improving sportive performances or for cardiovascular patients [13,14]. It is, thus, interesting to know how to control the level of nitrate. In the case of spinach and arugula, it is easier to produce a high nitrate content rather than reducing it. In this paper, we focus on reducing the nitrate content rather than increasing it.

Despite decades of research results available in literature on nitrate in vegetables [15], it remains difficult for growers to adhere to the general recommendations. Besides, not many recommendations have been formulated for vegetables grown in plant factory conditions, i.e., growing with only LED lighting as sole source of light. Among factors affecting the nitrate levels, light sum, temperature, and irrigation strategy are the most important [15]. In the past, without the possibility to control well the light, the only option was to control the irrigation. Soilless systems are being introduced to gain more control in phytochemical compound content and nutritional value [16]. A main advantage of cultivating vegetables soilless (i.e., hydroponically) in controlled environments is the capacity of growing them within a standardized quality range. This is due to the much lower disease pressure and better controlled climate, light settings, and mineral fertilization and irrigation (fertigation) [17]. Hence, the quality of the irrigation water is of great importance, especially in a hydroponic system [18]. Plants can take up nitrogen (N) as nitrate (NO_3^--N) and ammonium (NH_4^+-N) [19]. Previous research has shown that most plants fertigated with mainly NO_3^--N grow larger and give a higher yield compared to plants supplied with mainly NH_4^+-N [20]. This occurs probably because NO_3^--N increases plant photosynthesis more than NH_4^+-N does [21]. However, an increased total nitrate supply in the fertigation often increases nitrate accumulation in the leaves [22]. A common practice in soilless arugula cultivation is a change of fertigation to a lower EC during the last few days before harvest to achieve lower nitrate content. However, this goes at the expense of the growth rate [16], which will not be economically viable in a plant factory cultivation.

Low nitrate levels for leafy vegetables can also be achieved with a specific lighting strategy. In the plant, nitrate reductase (NR) can reduce NO_3^- to NO_2^-, which eventually will be reduced into amino acids to fulfill the nitrate reduction process [23,24]. The activity of NR can be influenced by light conditions, namely light spectrum, light intensity, and photoperiod (reviewed in [25]). The increased production of photosynthetic products (sugars) that come with the increased photosynthesis play a role in reducing nitrate accumulation, and the important role of PAR light has been reported for various vegetables [26]. It, therefore, seems wise to use an optimized light recipe during the growth phase when solar light is absent. However, many different effects of light spectrum have been reported on NR activity and total nitrate content. Lilo and Appenroth [27] claim in their review that red light has the highest capacity for reducing nitrate. On the other hand, Maevskaya and Bukhov [28] found a higher NR activity in radish under blue light, compared to red light, illuminated with the same light level and photoperiod. Furthermore, decreased levels of nitrate have been reported under blue light alone and for the combination of red and blue light, as compared to white light [29]. The direct effect of far-red has not been that widely investigated, but seems to decrease NR activity through a phytochrome-mediated pathway [30]. The relation between high PAR level and low nitrate content and vice versa has been reported in various leafy vegetables [26,31]. The increased production of photosynthetic products that come with the increased photosynthesis plays a role in the upregulated nitrate assimilation under higher light levels. The photoperiod length might play an important effect especially with short day plants, because nitrate is mainly processed during the day and accumulated during the night, when storage into the vacuoles is the most efficient. A preharvest extended day length with continuous red-light treatment successfully decreased nitrate assimilation in various vegetables [32,33]; however, this could be due to a photoperiod effect or light integral effect or both combined. During this extended day, nitrate storage in the vacuoles is inhibited and red photons, together with extra assimilated carbohydrates, promote nitrate reduction.

We are addressing all these mentioned hypotheses in this work for both baby leaf spinach and rucola. We include also a greenhouse trial to validate the concept of a dynamic light recipe in commercial growth conditions for lettuce.

2.5.2 MATERIALS AND METHODS

2.5.2.1 Plant Factory

All experiments were carried out at the Philips Lighting GrowWise research center in Eindhoven, the Netherlands. The total area for plant growth is 234 m^2 and is distributed among eight climate cells with four growth layers each and with each growth layer being divided into four sections, allowing many replicates with the same temperature and humidity conditions. The various climate cells are equipped with different types of LED lamps of variable spectrum (red, blue, green, far-red, and white). The light level in some of the sections can go up to 600 $\mu mol\, m^{-2}\, s^{-1}$. The lighting system we used in this work is based on Philips Greenpower LED research modules, which are spectrally controllable and dimmable. Each light section is calibrated in a defined rigorous procedure using a JETI spectrophotometer (Specbos 1201, JETI Tech. Instr. GmbH.). The symbols DRW and DRHB, respectively, define the light recipe made of deep-red white versus deep-red high-blue, where most photons provided are red. The spectra are composed of 10% and 35% blue light, respectively. For some trials, a small percentage of far-red light has been used. There are no significant temperature or humidity differences between the top and bottom layers because sufficient airflow cools the air in between the layers. The irrigation water has a temperature of 23°C. Seeds of spinach and rucola are sown in Rockwool substrates irrigated with a standard nutrient solution. For the growth of both spinach and rucola, the nutrient solution has a content of nitrate of 10–12 $mmol\, L^{-1}$ with an EC of 2 $mS\, cm^{-1}$ and a pH of 6. Additional micro- and macronutrient are dosed. The plant density during the germination phase was 1000 plants m^{-2}. Germination took place under standard breeder conditions. The preharvest light recipe used the standard DRW light with a 24 h photoperiod for 2 or 3 days, providing a total DLI of 20 and 25 $mol\, day^{-1}$ for spinach and rucola, respectively. This preharvest light strategy is a good practical choice directly applicable in commercial plant factories.

2.5.2.2 Plant Analysis

Plant's fresh and dry weights have been monitored to fulfill the optimum growth ($g\, mol^{-1}$ optimization). Results are not reported here. Plant sampling was done after 4 h of light during the day cycle at the same time for all samples to avoid effect of circadian changes in nitrate concentration. Samples were refrigerated and sent for analysis to an external laboratory. Nitrate content was analyzed by Eurofins Lab Zeeuws-Vlaanderen B.V (The Netherlands). Their method is in accordance with NEN-EN 12014-2. Sample extraction was done by MiliQ/HPLC water at 70–80°C and, after further processing, inserted into the Ion Chromatograph ICS 1100. Results were statistically analyzed using SPSS (ANOVA with Fisher's LSD).

2.5.3 RESULTS

2.5.3.1 Total Light Sum Effect on Nitrate

Optimizing the daily light integral (DLI) when growing a leafy crop is an important step in a light recipe optimization because it is important for optimizing photosynthesis as well as the light use efficiency. In the case of baby leaf spinach or arugula, when the photoperiod is limited to short day illumination to avoid bolting, it is only possible to increase the DLI by increasing the intensity of the light. The daily radiation integral was changed from 10 to 20 mol day^{-1} using a fixed photoperiod (16 h for spinach and 12 h for rucola) and a photosynthetic efficient light recipe (DRW). The graphs in Fig. 2.5.1A and B are showing the DLI dependence of the nitrate content in the freshly harvested leaves of baby spinach and arugula, respectively. The decrease as a function of increasing DLI is significant both for baby leaf spinach and cultivated rucola. In both cases, it is possible to achieve a value well below the EU regulation without changing the irrigation strategy by depriving the plants from nitrate and keeping an EC value around 2 mS cm^{-1}.

2.5.3.2 Light Spectrum Effect on Nitrate

Combination of red and blue or red and white LED lights can offer a well-optimized photosynthetic light to guarantee a low level of nitrate content. However, there are an infinite number of LED lighting spectra possible. Commercially available spectra may be composed with only white LEDs, which might differ in composition depending on the manufacturer. Others have a proportion of high blue and/or green. The amount of red light is particularly crucial for successful photosynthesis. In the spectra we use, the red photon fractions are always higher than 75% of the total PAR light, up to 95%. In addition, light recipes can include

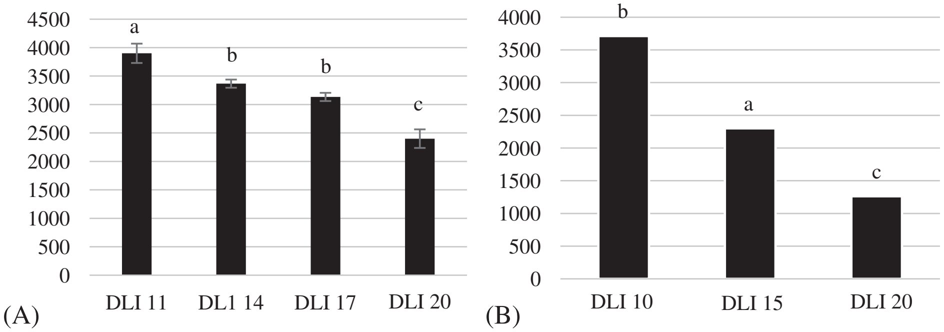

FIG. 2.5.1 (A) Nitrate content (in units of mg kg^{-1} FW) at harvest of baby leaf spinach under four different light recipes with a DLI 11, 14, 17, and 20 mol day^{-1}, respectively; (B) Nitrate content at harvest (first cut) of cultivated arugula under three different light recipes with a DLI 10, 15, and 20mol day^{-1}, respectively. All light spectra are composed of red and white LED light (RW).

sometimes far-red light in addition to the PAR. This far-red wavelength is also very much present in natural daylight, and therefore, also relevant for greenhouse cultivation under LED. We have particularly looked at the effects of far-red light. We tested first the effect of far-red on various lettuce cultivars from Rijkzwaan B.V. Fig. 2.5.2A shows the nitrate level in the harvested mature lettuces after 40 days of growth. For all cultivars and all the spectra, the nitrate level is sufficiently low to comply with EU regulation. Comparing the results for the different light recipes, the nitrate level is not always significantly different. The largest differences are seen for the Xandra and Expertise cultivars. Fig. 2.5.2B and C illustrate the results for spinach and wild arugula, respectively, harvested after 26 and 21 days of growth (first cut). Here as well, the standard lighting strategy we used to optimize growth has led to a nitrate level low enough to comply with EU regulation. Spectral effects are significant only for the baby leaf spinach grown under a high blue percentage.

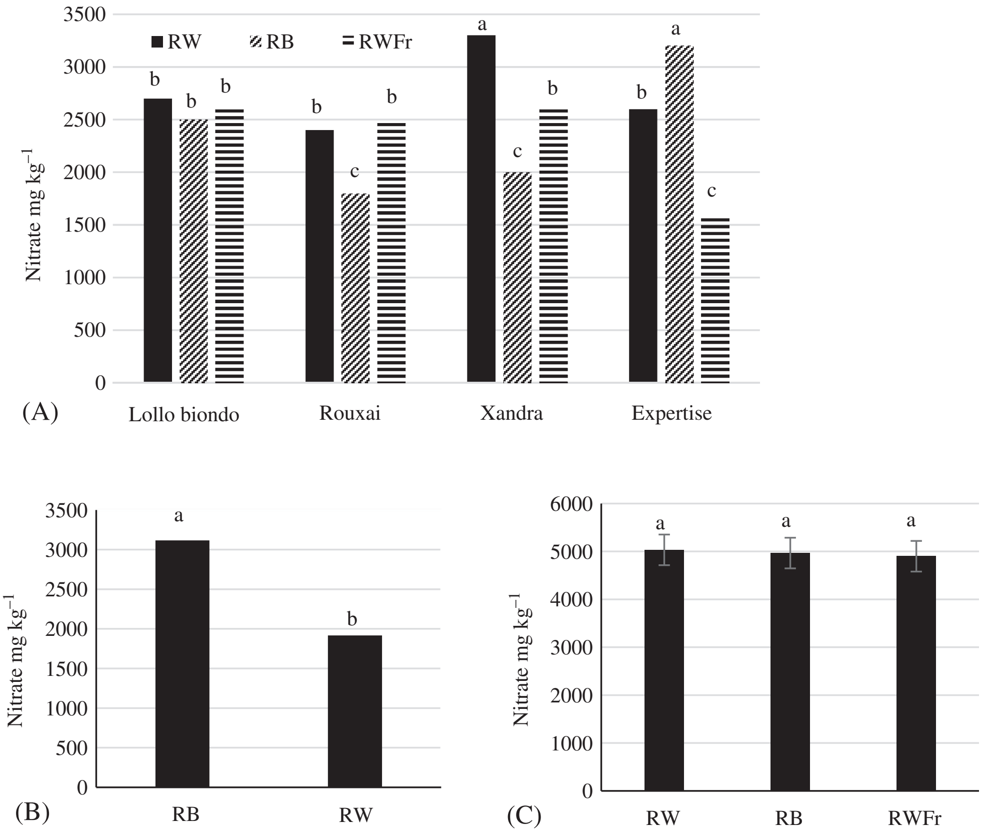

FIG. 2.5.2 (A) Nitrate content (in units of mg kg^{-1} FW) at harvest of various lettuce cultivars grown under three different light recipes (RW, RB, RWFr). The DLI was 12 mol day^{-1} with 18 h photoperiod; (B) Nitrate content at harvest of baby leaf spinach under two different light recipes (RB and RW); (C) Nitrate content at harvest (first cut) of wild arugula under three different light recipes (RB, RW, and RWFr).

2.5.3.3 Dynamic Light Strategy to Control Nitrate

According to previous publications on lettuce growth in greenhouses, it should be possible to reduce the nitrate level by applying a preharvest treatment using a longer light photoperiod (continuous) as a supplemental light or exclusively LED light [32,33]. We have applied this concept to lettuce grown in a vertical farm and in a greenhouse environment [9]. In the case of lettuce, it was never a challenge to reduce nitrate by using a lighting strategy efficient for growth. However, for baby leaf spinach and arugula, this may become necessary as those crops may grow more efficiently at lower DLI than the DLI required for a low nitrate level. In order to optimize light use efficiency and low nitrate, a dynamic lighting strategy to reduce nitrate may become necessary. In Fig. 2.5.3A, a continuous preharvest light is applied for 3 days on lettuce type Lollo Biondo. The results show that, despite the already low nitrate levels, the final nitrate at harvest can be reduced significantly compared to control. However, this seems to only work for preharvest light containing red. Indeed, for the 100% blue (RW-Pre Blue), nitrate levels remain similar. In Fig. 2.5.3B and C, a continuous light (DRW or DRHB) is applied as a preharvest treatment for baby leaf spinach (48h) and arugula (72h). The reduction in nitrate level for arugula is up to 50% which brings the nitrate level to a very low level. For baby leaf spinach, the spectrum composed of RW seems again to be favorable for a lower nitrate level; however, after a preharvest continuous light, the results comparing both spectra are not significant. In the case of arugula, the spectral effect of the control or

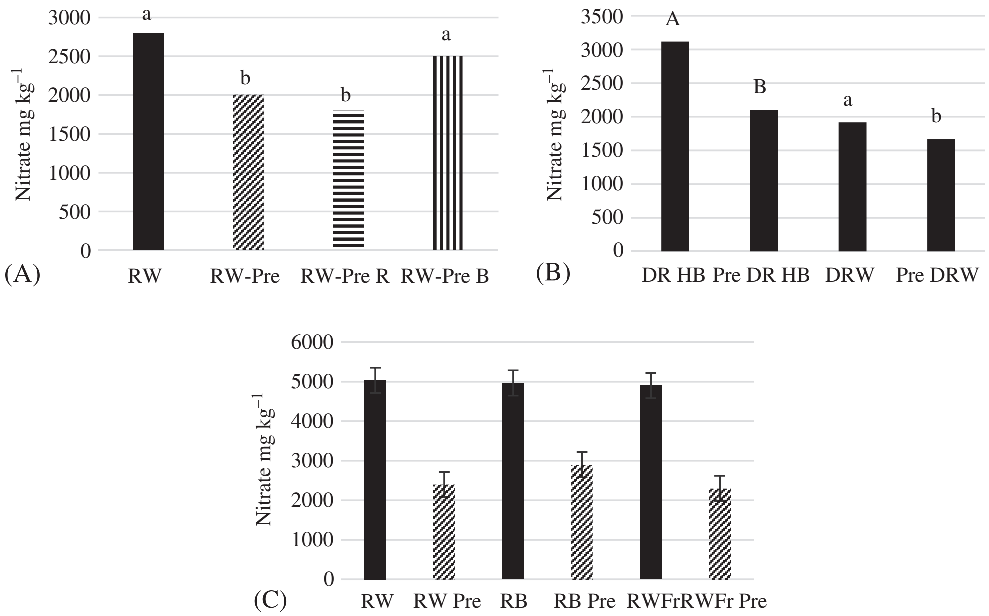

FIG. 2.5.3 (A) Nitrate content (in units of mg kg^{-1} FW) at harvest of various lettuce cultivars grown under three different light recipes (RW, RB, RWFr). The DLI was 12 mol day^{-1} with 18 h photoperiod; (B) Nitrate content at harvest of baby leaf spinach under two different light recipes (RB and RW); (C) Nitrate content at harvest (first cut) of wild arugula under three different light recipes (RB, RW, and RWFr).

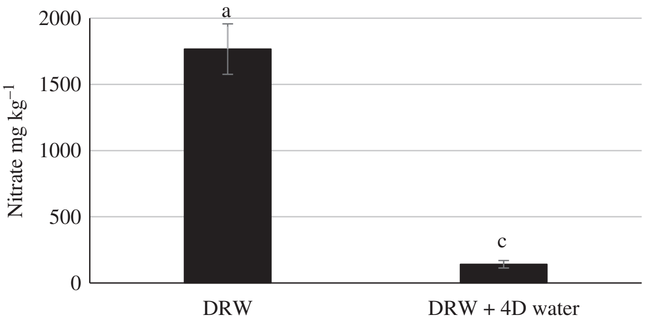

FIG. 2.5.4 Nitrate content (in units of $\mathrm{mg\,kg^{-1}}$ FW) at harvest of baby leaf spinach under a similar control light (DRW), but with irrigation water with a different nutrient composition (right) for the last 4 days of growth (irrigation water without nutrients).

preharvest treatment is not significant and all spectra can be used to reach a low nitrate level. In addition, the continuous preharvest light duration did not significantly induce bolting of arugula or spinach.

2.5.3.4 Irrigation and Light Strategy to Further Reduce Nitrate

When growing lettuce or other vegetables in a plant factory, it is important to optimize the composition of the nutrients in the irrigation water. While the irrigation water is recirculating, its composition should be adjusted constantly to avoid overdosing or depletion of the nutrients: first, in order to achieve an equal leaf minerals and vitamin content and, second, in order to not decrease the growth potential. From the results shown in Fig. 2.5.4, we observe the effect of applying a preharvest irrigation composed of water only (nutrients being washed out) for the 4 last days of spinach growth. Since the growth before harvest is exponential, all the new leaves of baby spinach that are synthesized do not contain much nitrate. On average, the nitrate level was found to be below $500\,\mathrm{mg\,kg^{-1}}$. However, a 20% decrease in yield was observed compared to the control.

2.5.3.5 Plant Density Effect on Nitrate Content

When optimizing growth efficiency in a plant factory, plant spacing is an important factor. Between germination and final harvest, we can have one to three respacing in the process with the first one being the transplanting just after germination. In order to optimize the maximum use of space and light interception by the plants, crop morphology and growth speed need to be considered. A low plant density will reduce the $\mathrm{g\,mol^{-1}}$ and, therefore, the growth efficiency, while a high density will increase it (because of the higher light interception). However, too high a density may also level off and reduce the $\mathrm{g\,mol^{-1}}$. A higher density will have an impact on light interception and, therefore, indirectly might have an impact on final nitrate content. The results summarized in Table 2.5.1 show that the growth efficiency ($\mathrm{g\,mol^{-1}}$) decreases with increasing plant density, but at the same time the nitrate content also decreases suggesting that a higher plant density is not favorable for keeping nitrate levels low. Plant density and final nitrate content at harvest are, therefore, closely related (Fig. 2.5.5).

TABLE 2.5.1 Radiation-Use Efficiency (RUE), Yield, and Nitrate Content for Coltivata Planted at 1500 and 750 plants m^{-2}, 15 Days after Sowing

Density (plants m^{-2})	RUE ($g\,mol^{-1}$)	Yield ($g\,m^{-2}$)	Nitrate Content ($mg\,kg^{-1}$)
1500	4.12 ± 0.31a[a]	722 ± 55a	3300 ± 283a
750	2.44 ± 0.16b	427 ± 29b	2200 ± 0b

[a] *Different letters mean significant differences* ($P = .05$) *between treatments.*

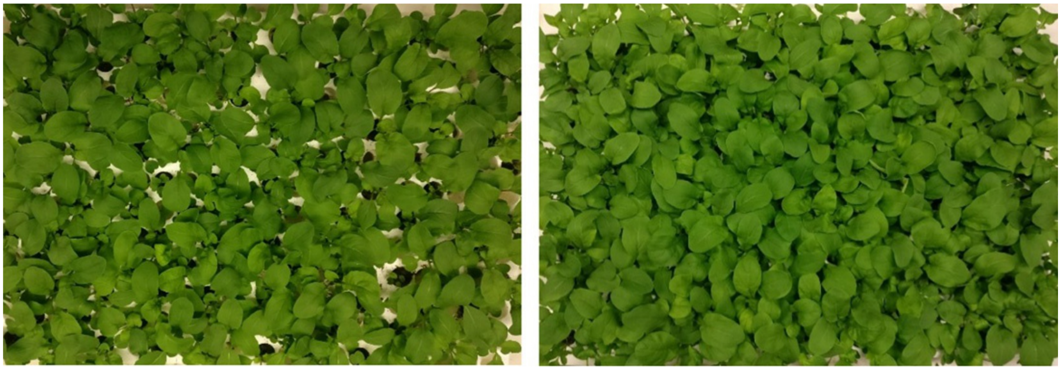

FIG. 2.5.5 Visual difference between the two densities. Cultivated arugula grown at 750 plants m^{-2} (left image) have more space, compared to plants grown at 1500 plants m^{-2} (right image).

2.5.3.6 Comparing Greenhouse and Vertical Farming

Application of this research to North European commercial greenhouse cultivation has been done during winter time for growing lettuce using HID supplemental lighting with 16h illumination per day. Grown in these conditions, the nitrate content at harvest is always very high in frisée lettuces (*cv* Exact from Rijkzwaan) when a typical daylight contribution is only a few mol per day during winter in Northern European countries. Applying a 22 h photoperiod HID lighting or LED lighting (at 200 $\mu mol\,m^{-2}\,s^{-1}$) for 5 days before harvest was used to decrease the nitrate level. The same crop was grown in a plant factory under DRB with the same DLI, growth history, and photoperiod as in the greenhouse. The only differences were the light distribution over the day, climate settings (temperature and humidity more stable and higher), and irrigation formula (similar EC, but different ratios of nutrients). The results in Fig. 2.5.6 show that, with an extended photoperiod using the LED light, there is a significantly higher reduction of the nitrate level compared to the HID light, implying that spectral differences between the two light sources play a role in nitrate reduction. We also observed that this crop grows with a nitrate level below 1000 $mg\,kg^{-1}$ in the vertical farming condition under similar light levels and a similar 5 days preharvest treatment with extended photoperiod. This shows that the global growth conditions (irrigation, climate, and light) are to be considered when using a nitrate reduction strategy. In addition, the growth history is important in a greenhouse where the light level changes frequently and older leaves grown under less light (less than 8 mol day^{-1}) might not be exposed sufficiently to light during the last

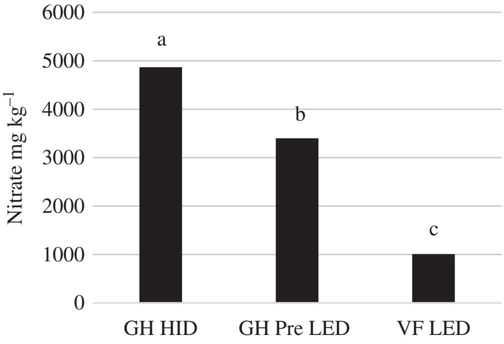

FIG. 2.5.6 Nitrate content (in units of mg kg^{-1} FW) content at harvest of frisée lettuce under HID illumination (GH HID) or LED illumination (GH Pre LED) in a greenhouse with an extended photoperiod of 22 h the last 5 days before harvest compared to plant factory growth under solely LED illumination and controlled climate (VF LED) with similar growth conditions.

5 days of preharvest light due to shading of the new leaves in the center of the lettuce and/or neighboring plants. This simple example shows that a combination of different parameters can interact and influence the growth results and it is not always straightforward to compare greenhouse conditions to the well-controlled and stable environment of plant factories.

2.5.4 DISCUSSIONS AND CONCLUSIONS

In this research, we show that, by optimizing the light quantity (DLI) only, a good control of the nitrate level can be achieved in vegetable crops known for their high nitrate accumulation. This result is in accordance with previously observed effects of light level [33].

Nitrate levels were not significantly affected by the spectrum when varying the dose of far-red from 0% to 25% of the PAR light contribution. However, when a light recipe is used with a higher percentage of blue than our standard 12%, we observed for some species of baby leaf spinach a higher nitrate level. Far-red is used as an additional spectral contribution to PAR light (in our experiment, we did not vary the PAR level). When increasing the proportion of blue percentage while keeping the PAR level constant, the red fraction is reduced which may lead to an effect on photosynthesis efficiency and, therefore, on nitrate levels. In cultivated or wild arugula, the effect of a higher blue percentage had no significant effects on nitrate level during growth or with preharvest treatments. In the case of baby leaf spinach, the high blue percentage produced a higher nitrate level, but applying a continuous preharvest light reduced the nitrate level for both treatments with high and low blue percentage. It seems that an optimized DLI in PAR light is the determinant factor controlling the nitrate level in the harvested produce. However, when comparing HID to LED, the nitrate reduction is significantly better with the LED source. Therefore, a photosynthetic efficient light source (high red photon fraction) enables a more successful nitrate reduction.

Both for spinach and arugula, a nitrate level lower than 1500 mg kg^{-1} could be achieved by optimizing the light recipe only without affecting the yield and visual quality parameters or shelf-life. Using a preharvest light strategy brings also benefits in the case of crops requiring a short photoperiod. Combining the light recipe with a dynamic irrigation strategy and a lower crop density can further lower nitrate levels, but it will impact production yield negatively.

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CHAPTER

2.6

Photoreceptor-Mediated Plant Development

Yoshito Oka[*], *Kazuhiko Yamamoto*[†]

[*]**Basic Forestry and Proteomics Research Center, Fujian Agriculture and Forestry University, Fuzhou, China** [†]**Tagajyo Factory, MIRAI Co., Ltd., Miyagi, Japan**

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2.6.1 INTRODUCTION

Plants use light energy for photosynthesis, a process that fixes carbon dioxide to produce organic compounds that are essential for life. Plants also recognize light as information to optimize their morphology and metabolism for efficient photosynthesis under a fluctuating light environment in nature. Accordingly, various growth and developmental processes in plants are affected by light intensity and quality and day length. Importantly, such light-mediated adaptive responses, termed photomorphogenesis, include traits that are important for plant factory with artificial lighting (PFAL).

Plant Factory using Artificial Light
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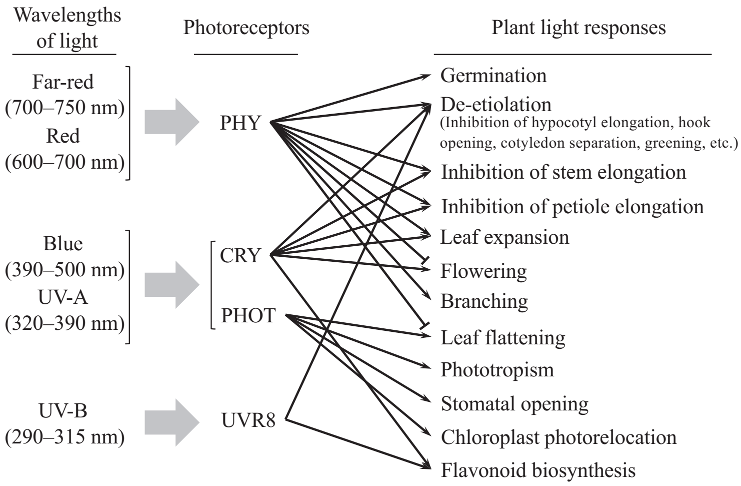

FIG. 2.6.1 Photoreceptor-mediated responses. Plants use phytochrome (PHY), cryptochrome (CRY), phototropin (PHOT), and UV RESISTANCE LOCUS 8 (UVR8) to regulate a wide range of plant light responses. Arrows and bar-headed lines represent promotion and inhibition, respectively.

Photoreceptors, chromoproteins that absorb specific wavelengths of light and convert them into signals that regulate biological processes, play crucial roles in modulating photomorphogenesis. Higher plants use red/far-red light-absorbing phytochrome (PHY); UV-A/blue light photoreceptors, including cryptochrome (CRY), phototropin (PHOT), and others; and UV-B-absorbing UV RESISTANCE LOCUS 8 (UVR8) (Fig. 2.6.1). Although the biochemical characteristics, functions, and signaling mechanisms of these photoreceptors have predominantly been clarified in the model plant *Arabidopsis thaliana* (Arabidopsis), these photoreceptors and their signaling components exist in all angiosperms with publicly accessible genomes. Thus, they also play important roles in regulating the growth, morphology, and metabolism of plants used for PFAL. In this section, we describe the properties, functions, and signaling mechanisms of photoreceptors in Arabidopsis and discuss the functions of photoreceptors and appropriate light conditions that regulate important traits for PFAL.

2.6.2 PROPERTIES, FUNCTION, AND SIGNALING MECHANISM OF PHOTORECEPTORS

2.6.2.1 Phytochrome

Red and far-red light-absorbing PHYs are responsible for a number of plant light responses (Fig. 2.6.1). PHYs have two spectrally distinct isoforms, a red light-absorbing form of PHY (Pr) and a far-red light-absorbing form of PHY (Pfr), which display a characteristic photoreversibility between them [1] (Fig. 2.6.2). PHYs are activated by red light-induced conversion from Pr to Pfr, but conversely, they are inactivated by far-red light-induced transformation from Pfr to Pr. Among the five PHYs (phyA-phyE) encoded in the Arabidopsis genome, phyA

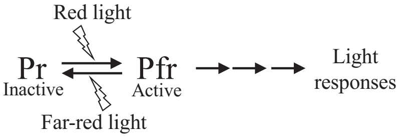

FIG. 2.6.2 Phytochrome photoreversibility. Phytochrome (PHY) displays photoreversibility between a red light-absorbing form of PHY (Pr) and a far-red light-absorbing form of PHY (Pfr). Red light activates PHY by converting Pr to Pfr to trigger light responses. By contrast, far-red light inactivates PHY by converting Pfr to Pr.

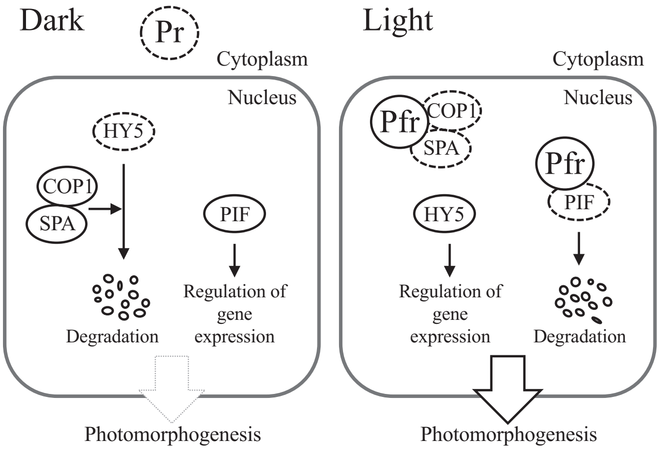

FIG. 2.6.3 A model depicting phytochrome signal transduction mechanism. In the dark, phytochrome (PHY) is localized in the cytoplasm in its Pr state. COP1/SPA complex leads to the degradation of HY5. Stable PIF proteins regulate the gene expression to suppress photomorphogenesis. Upon light exposure, PHY in its Pfr status gets into the nucleus where it leads to the inactivation of COP1/SPA complex and the degradation of PIF. Stable HY5 proteins regulate the gene expression to promote photomorphogenesis.

and phyB play major roles. phyA and phyB have partially redundant or antagonistic functions in regulating seed germination and de-etiolation (inhibition of hypocotyl elongation, cotyledon opening, greening, etc.). However, they generally function under different light environments: phyA acts as a hypersensitive photoreceptor under dim light, where very low Pfr accumulates, while phyB predominantly acts under bright environments. In addition, phyB plays critical roles in regulating light responses during vegetative growth. Importantly, phyB is a major PHY species that regulates important traits for PFAL, such as suppression of stem and petiole elongation; promotion of branching and leaf morphology, including leaf expansion; and promotion of leaf curling.

When PHYs absorb light, they translocate from the cytoplasm to the nucleus, where they regulate the expression of a number of genes that induce photomorphogenesis, primarily through two distinct pathways: the PHYTOCHROME INTERACTING FACTOR (PIF) pathway and the CONSTITUTIVE PHOTOMORPHOGENIC 1 (COP1)/SUPRESSOR OF PHYA-105 (SPA) complex pathway [1] (Fig. 2.6.3). PIFs are members of a transcription factor family that specifically interact with Pfr of phyB. While PIFs repress photomorphogenesis in the dark, PHYs de-repress photomorphogenesis by degrading PIFs through direct interaction upon light activation. On the other hand, the COP1/SPA complex, an E3 ligase that is responsible for protein degradation, also acts as a negative regulator of photomorphogenesis. In the dark, the COP1/SPA complex recognizes transcription factors that positively regulate photomorphogenesis, such as ELONGATED HYPOCOTYL 5 (HY5), and promotes its degradation. Upon light absorption, Pfr of PHYs directly binds to the COP1/SPA complex to inactivate its E3 ligase activity, thereby promoting HY5 protein accumulation and subsequent photomorphogenesis.

2.6.2.2 Cryptochrome

CRYs are flavoproteins that are activated upon UV-A/blue light absorption. Photoactivated CRYs are partially inactivated by green light exposure. However, no consensus has been reached on this partial photoreversibility of CRYs. CRYs mediate a wide range of plant light responses, including inhibition of stem elongation, leaf expansion, flowering, etc. [2] (Fig. 2.6.1). Remarkably, CRY-mediated physiological responses largely overlap those mediated by PHYs, although CRYs and PHYs act under different wavelengths of light. Two CRYs, CRY1 and CRY2, partially regulate overlapping physiological responses under blue light in Arabidopsis.

Consistent with the fact that CRYs and PHYs mediate similar physiological responses, CRYs also regulate gene expression in the nucleus through the PIF pathway and the COP1/SPA pathway (Fig. 2.6.4). More specifically, upon blue light absorption, CRYs form a dimer to become active. Photoactivated CRYs directly interact with PIFs to inactivate their transcriptional activity, and in parallel, they also inactivate the COP1/SPA complex by direct binding, which promotes HY5 accumulation [2]. These direct and indirect regulatory processes of transcription factors by CRYs trigger photomorphogenesis. Additionally, CRY2 binds to another class of transcription factors to promote flowering [2].

2.6.2.3 Phototropin

PHOTs regulate phototropism, stomatal opening, chloroplast photorelocation, and leaf morphology in response to UV-A/blue light [3] (Fig. 2.6.1). These responses are required for efficient photosynthesis. In fact, Arabidopsis PHOT-deficient mutants reportedly showed drastic growth defects under weak light conditions. Two PHOTs, phot1 and phot2, exhibit some functional differences depending on the physiological response in Arabidopsis. However, they generally have overlapping functions under different light environments: phot1 acts under a broad range of blue light intensity, whereas phot2 functions mostly under a higher intensity of blue light.

PHOTs are plasma membrane-associated protein kinases. Upon photoactivation, PHOTs undergo autophosphorylation and phosphorylate their signaling partners to transduce a

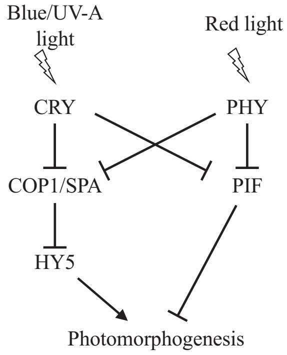

FIG. 2.6.4 Phytochrome and cryptochrome share common signaling pathways. Phytochrome (PHY) and cryptochrome (CRY) induce photomorphogenesis through PIF pathway and COP1/SPA pathway. Arrows and bar-headed lines represent promotion and inhibition, respectively.

signal [3]. PHOTs directly phosphorylate BLUE LIGHT SIGNALING 1 and activate plasma membrane H^+-ATPase in guard cells to promote stomatal opening. However, the phototropin substrates that have essential roles in regulating other PHOT-mediated responses remain unidentified.

2.6.2.4 UV Resistance Locus 8

Although high levels of UV-B cause growth defects in plants, low levels of UV-B promote photomorphogenesis. Recently, UVR8 was identified as a photoreceptor that regulates UV-B-induced photomorphogenesis [4]. UVR8 regulates the expression of genes that are not only necessary for cell expansion and photosynthesis, but also genes that are involved in DNA repair and biosynthesis of flavonoids, such as anthocyanin, which prevents damage from UV-B [4] (Fig. 2.6.1). The UVR8 protein forms a homodimer in the cytoplasm in the absence of UV-B, but dissociates to become active in response to UV-B [4]. UVR8 monomers accumulate in the nucleus and directly interact with COP1 to modulate its function [4].

2.6.3 APPLICATION OF PHOTORECEPTOR STUDIES FOR PFAL

The development of light-emitting diodes with various wavelengths made it possible to design different light spectra with different purposes. Thus, appropriate light conditions are important to secure the productivity and quality of products in PFAL. Here, we discuss photoreceptor involvement in important traits in PFAL, such as seedling growth, leaf morphology, and branching, and also discuss the conceivable light conditions that are suitable for these traits. This could aid in selecting a light source and lighting scheme.

2.6.3.1 Seedling Growth

Spindly growth of seedlings often becomes problematic in PFAL. It not only leads to an unfavorable product shape, but also decreases productivity. An inadequate wavelength, insufficient intensity, or inadequate irradiation period of light can cause spindly growth. PHYs and CRYs inhibit hypocotyl and stem elongation in Arabidopsis and other plants. Consistently, spindly growth is inhibited under sufficient red and blue light conditions. By contrast, far-red light supplementation promotes spindly growth because far-red light decreases the ratio of active Pfr to the total amount of phyB (Fig. 2.6.2). Green light also inhibits the effect of blue light to some extent on the inhibition of hypocotyl elongation in Arabidopsis by inactivating CRYs, although this effect has not been seen in other reports. While the impact of red and blue light on seedling growth depends on the plant species and cultivar, increasing the percentage of blue light in the light spectrum could efficiently inhibit hypocotyl elongation in several plants, such as lettuce and kidney bean [5,6]. Moreover, UVR8 strongly promotes inhibition of hypocotyl elongation in the presence of weak UV-B in Arabidopsis, and the UV-B-induced response can be observed in various plant species [7]. Thus, it may be worth using UV-B in addition to blue and red light to effectively avoid spindly seedling growth.

2.6.3.2 Leaf Morphology and Branching

Controlling leaf morphology and branching is a prerequisite for PFAL due to space limitations in PFAL. It is also important to satisfy the needs of various customers. PHYs and CRYs play important roles in the regulation of leaf size and thickness. Accordingly, red and blue light are effective at controlling these responses. Under sufficient red and blue light conditions, plants suppress petiole elongation and promote the formation of large, thick leaves. Conversely, under insufficient red and blue light conditions or low R/FR ratio conditions, plants have small and thin leaves with elongated petioles. On the other hand, PHOT and phyB act antagonistically in regulating leaf flattening: PHOTs promote leaf flattening, but phyB promotes downward leaf curling. In fact, far-red light supplementation can inhibit leaf curling by suppressing the function of phyB. However, it seems reasonable to promote leaf flattening by increasing the blue light intensity to enhance PHOT function rather than by far-red supplementation because suppression of phyB function leads to undesirable effects on other traits. By contrast, red light predominantly promotes branching by activating phyB in Arabidopsis. Indeed, red light supplementation can increase the number of branches in several plant species [8–10]. Thus, careful attention must be paid in determining the balance between blue and red light so that plant architecture is regulated in accordance with the intended purpose.

2.6.4 CONCLUDING REMARKS

Extensive studies on plant photoreceptors in Arabidopsis have led to an understanding of plant light responses at the molecular level. In particular, PHYs and CRYs have been shown to play major roles in regulating several important traits for PFAL. PHOTs are thought to contribute to optimal photosynthesis under light conditions in PFAL. In addition, UVR8 plays an important role in regulating not only photomorphogenesis, but also the production of secondary metabolites in response to UV-B in Arabidopsis and, possibly, in other various plant species [11–13]. Understanding the properties of photoreceptors and their involvement in important traits would provide useful information during the selection of light conditions to improve productivity and quality of products in PFAL. From another point of view, knowledge about photoreceptor signal transduction may provide additional clues to improve performance in PFAL. For example, Arabidopsis mutants of components in the PHY/CRY signal transduction pathway, such as COP1, SPAs, and PIFs, exhibit a hypersensitive response to light. Thus, selective breeding by targeting such genes or certain loci may improve plant morphology and light responses and, subsequently, contribute to reducing electricity consumption in PFAL. Since photoreceptor research is compatible with PFAL, a deeper understanding of light signal transduction mechanisms and affirmative action to adopt knowledge from photoreceptor research to engineering will undoubtedly enable further improvements in the productivity and quality of products in PFAL.

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CHAPTER

3.1

Optimization of Growth Environment and Development of Technology to Control the Concentration of Functional Components

Teruo Wada

Graduate School of Life and Environmental Sciences, Osaka Prefecture University, Sakai, Japan

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3.1.1 INTRODUCTION

The number of plant factories is increasing now. In 2017, it was reported that the numbers were 197 with fully artificial lightings, 126 with only the sunlight, and 31 with the sunlight and supplemental lightings in Japan [1]. Furthermore, in case of the plant factory with fully artificial lightings, it was estimated that the market scale of facilities, systems, and devices associated with plant factory was about 42 billion yen, and the market scale of the products

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in the plant factories was about 34 billion yen in 2015. They are expected to be 9.7 billion dollars and 22 billion dollars in 2018, respectively [2,3]. Now, most of plants produced in plant factory are lettuces. Though the cost producing lettuces is decreasing, it was estimated about 77 yen per a 100 g plant in the plant factory with fully artificial lightings, even though it was 50 yen in hydroponics in the greenhouse [4]. Further cost reduction is desired and it was also focused on the production of higher valued plants such as new functional plants or the plants highly containing functional components which can be sold with higher price. Therefore, we are developing the optimum environments for growing some kinds of vegetables and the new technology to control the functional components in the plants. We have already conducted the experiments for growing strawberries, low nitrate lettuces, or new functional vegetables such as Ashwagandha or Botan-bofu. This chapter described the procedures to search the optimum environments and technologies to control the concentration of the functional components when new plants are tried to grow in the plant factories with fully artificial lightings.

3.1.2 OPTIMIZATION OF GROWTH ENVIRONMENTS

It is important that the optimum environments from germination to harvest are clarified, the methods and systems of cultivation are established, and new methods of cooking or eating are developed, when a new plant is tried to grow in a plant factory. It will be needed to clarify the factors in each development stage of the plants shown in Table 3.1.1.

3.1.2.1 Germination

Temperature, water, oxygen, and light affect the germination of plants. The most important factor is the temperature. The optimum temperature for germination will be gotten by germination test under 20–30°C. Furthermore, it is desirable to check the kinds of media (urethane form or vermiculite, etc.) for germination and its water contents, and even with or without light. If the germination rate is too low or the seeds do not germinate uniformly, testing pretreatment shown in Table 3.1.2 should be considered.

3.1.2.2 Aerial Environments for Growth

Aerial environments are basically decided by measuring photosynthetic rate associated with temperature, light intensity, and CO_2 concentration. Actually, photosynthetic photon flux density (ppfd) is approximately limited between 100 and 300 $\mu mol\,m^{-2}\,s^{-1}$ in a plant factory. So, main factor affecting photosynthesis is temperature. Fig. 3.1.1 shows an example of the temperature—photosynthesis curve in a certain plant at the 100 and 300 $\mu mol\,m^{-2}\,s^{-1}$ of ppfd. Generally, the optimum temperature for photosynthesis is affected by light intensity, and the optimum temperature ranges wider and become lower as the light intensity is lower. The photosynthesis is also affected by spectrum distribution of the light. Therefore, the photosynthetic rate should be measured under the same light intensity and spectrum as the light used in the actual plant factory. If they have not decided yet, the photosynthetic rate should be measured under at least 2 light intensity. Day length is also an important factor.

TABLE 3.1.1 Environmental Factors to be Optimized in Each Stage

Stage	Environmental Factor	Method of Research
Seeding	Temperature	
	Moisture	Germination test
	Light or dark	Treatments of forcing germination
	Pretreatment	
Seedings	Light	
	Intensity	
	Spectral distribution	Photosynthetic rate
	Day length,	Morphometry
	Temperature	Growth analysis
	Light period	Condition of flower-bud initiation
	Dark period	Cultivation test
After transplanting	CO_2 concentration	Nutrient uptake
	Humidity	Concentration
	Nutrient solution	Composition
	Concentration	Ingredient in plants
	Nutrient composition	
	Plant density	
Harvest	Harvest method	Measurement of plant growth rate
	Size	Analysis of growth duration and cost
	Shape	Cooking recipe

Though longer day length increases accumulated photosynthate, it needs higher cost of electric power and sometimes causes some problem such as abnormal shape of leaves with over-accumulation of starch or active oxygen and flower stork formation in long-day plants such as spinach. Finally, light intensity and day length will be decided with consideration of the cost of electric power and the plant growth. The optimum temperature during dark period is affected by the amount of photosythate accumulated during light period. The more the accumulated photosynthate, the higher temperature during dark period would give higher growth. However, it must be considered that too high temperature during dark period could cause some problem physiologically. For example, the temperature more than 20°C during dark period causes stem elongation with flower bud initiation in lettuces. Though it is ideal to measure the relationship between the starch content and the temperature during dark period, the experiment combined with various temperatures during light and dark periods is conducted usually.

TABLE 3.1.2 Examples of the Treatments for Forcing Germination or Uniform Germination

Treatments	Methods
Seed selection	Uniformizing the seed size mesh, wing, salt solution, etc.
	Removal of empty seeds
Injuring seed coat of hard seeds	Removing seed coat softening seed coat by dipping in acid solution
	Injuring seed coat
Removing seed coat of achene	Seeds with removed apparent seed coat, which is the fruit of achene, is sold as naked seeds.
	ex. Spinach
Hardening	Softening seed coat by repeatedly watering and drying
Washing	Washing away germination inhibitor contained in the seed coat
Breaking dormancy	Keeping seeds under low or high temperature for a certain period after or before watering to the seeds.
Osmotic priming	Washing and drying seeds after osmotic treatments as dipping the seed in the solution with approximately -1.0 Mpa (0.4 mol L^{-1}) of PEG or salt
	ex. Tomato
Matric priming	Keeping seeds in a medium (vermiculite) with 10%–20% of water content for a few days
Growth regulator	Dipping seeds in the solution with 50–100 ppm of gibberellic acid or kinetin for 24 h
	ex. Eggplant

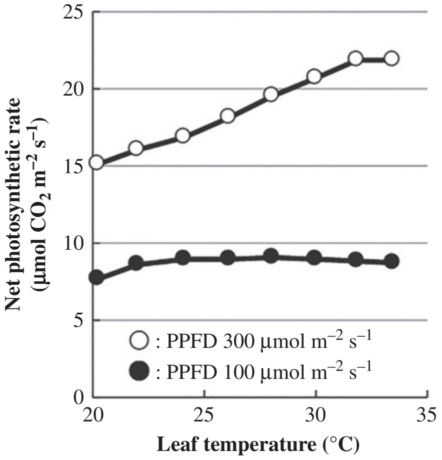


FIG. 3.1.1 An example of temperature—photosynthetic rate curve in a certain plant.

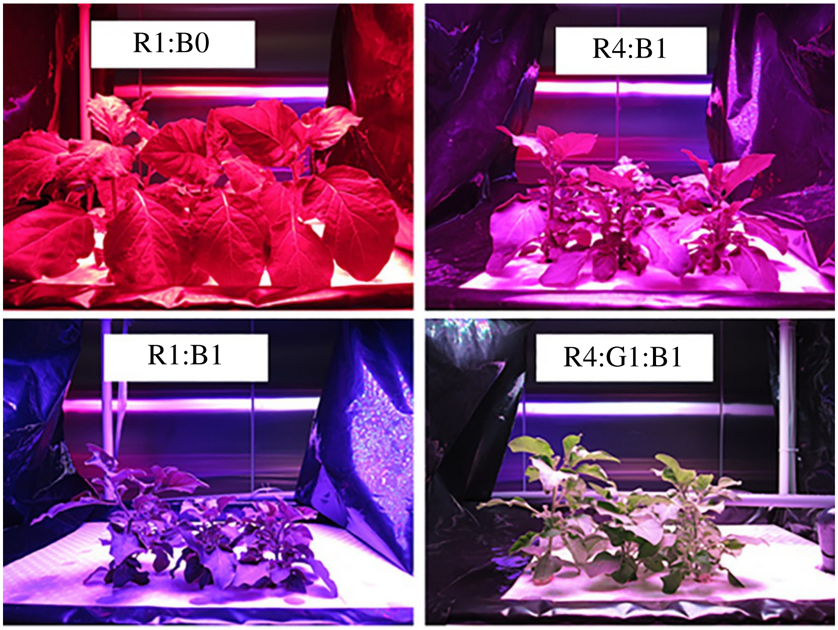


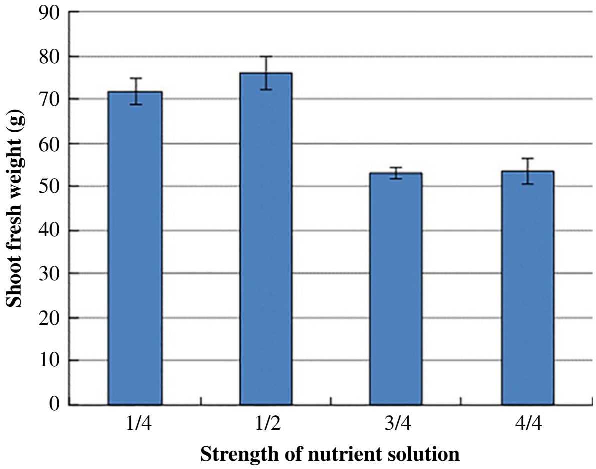
FIG. 3.1.2 An example of the effects of the RGB ratio on the plant growth.

Light quality is also an important factor because using LED for light source is popular now. Firstly, ratio of red (600–700 nm) and blue (400–500 nm) is considered. It affects the shape of plant strongly. Secondly, addition of green (500–600 nm), which affects plant growth or concentration of some ingredients, or far red (700–800 nm), which affects leaf expansion associated with cell elongation, is considered whether the addition of them increases plant growth or not. An example of the experiment of light quality is shown in Fig. 3.1.2. The plant grown with only red light had wider leaf and taller stem. The plant shape and quality have to be also considered in commercial production. The cultivation experiments with various ratio of these spectrum will be needed under the same ppfd or the same electric consumption. Recently, use of white LED, which is made with blue LED tip and fluorescent materials, is becoming popular. Also in this case, many kinds of white LED lamps with various spectral distribution by changing the kind or ratio of fluorescent materials have been developed.

3.1.2.3 Composition of the Nutrient Solution

In order to make the nutrient solution with the best composition for the plant growth, the experiments under various concentration of the standard nutrient solution are conducted and apparent nutrient uptake by plants is determined. A result of lettuce is shown in Fig. 3.1.3. In this experiment, the concentration of major elements was changed as indicated by strength, but the concentration of minor elements is constant in all treatments. It is shown that the plant growth was the highest in half strength of the nutrient solution. A result of more detailed

FIG. 3.1.3 Effect of the concentration of the nutrient solution on the shoot fresh weight of lettuce.



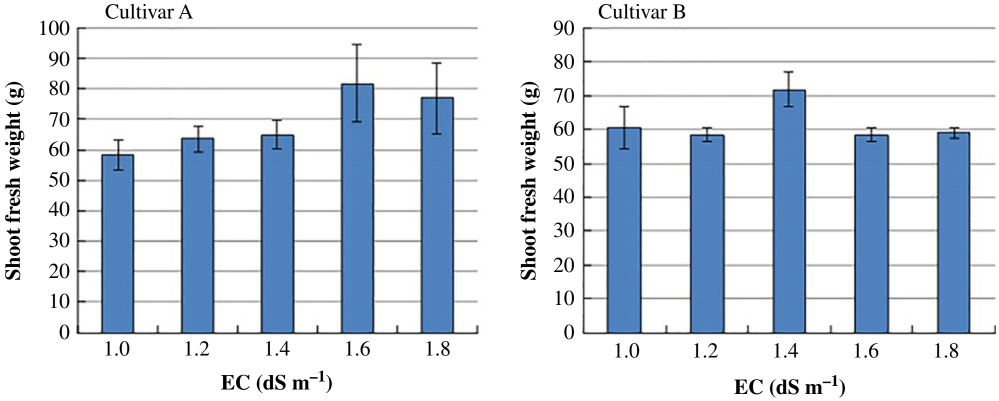


FIG. 3.1.4 Effect of the concentration of the nutrient solution on the shoot fresh weight of two cultivars of lettuce.

experiments with two different cultivars of lettuce was shown in Fig. 3.1.4. It is shown that the nutrient concentration for the best growth was different with cultivar. The apparent nutrient uptake by plants (described in Chapter 1.1) in the experiments shown in Fig. 3.1.3 was shown in Fig. 3.1.5. The apparent nutrient uptake by plants under the half strength of the nutrient solution, in which plant growth was the best, was below: NO_3^-: 11, $H_2PO_4^-$: 1, K^+: 7, Ca^{2+}: 1.3, Mg^{2+}: 0.8 mmol L^{-1}. The nutrient composition between the nutrient uptake and the nutrient solution for the best growth is not always same as described in the Chapter 1.1. Based on this composition, the best composition will be searched. It is also indicated that lettuce absorbs much ammonium ion in Fig. 3.1.5. However, higher concentration of ammonium ion often causes the tip-burn of leaves and decreases pH of the nutrient solution. So, further experiments with various ratios of nitrate and ammonium under the same total nitrogen concentration should be conducted.

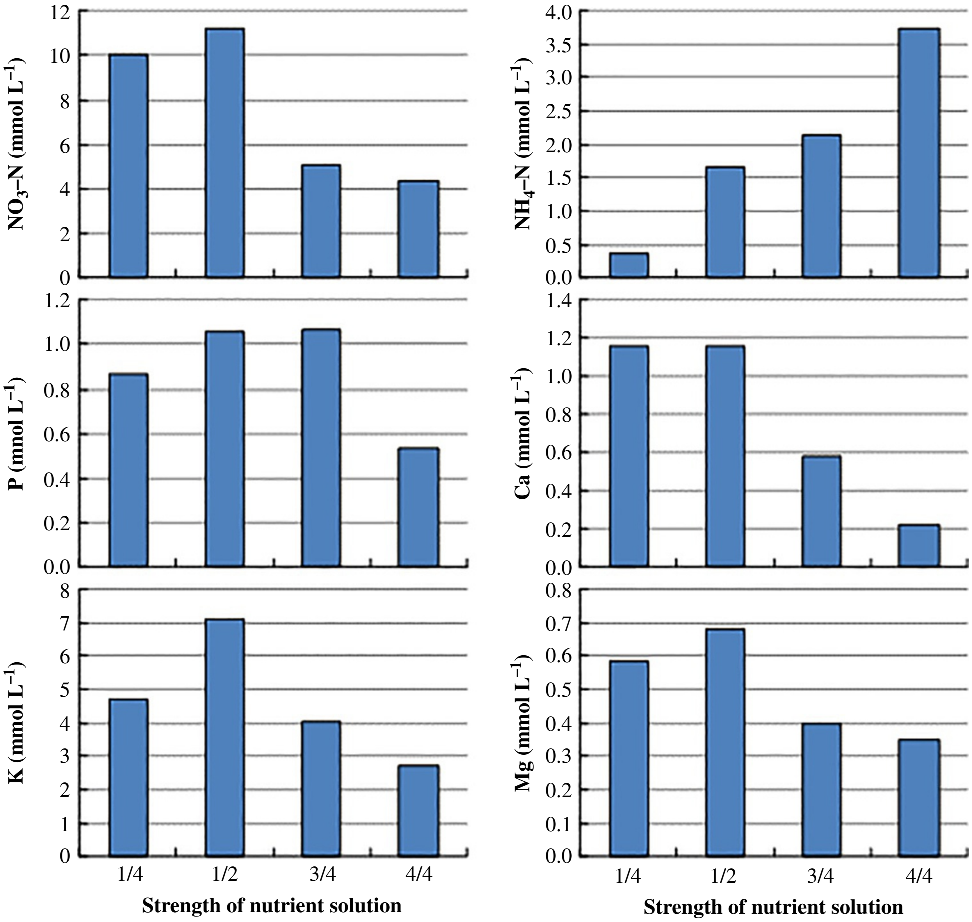


FIG. 3.1.5 Effects of the concentration of the nutrient solution on the apparent nutrient uptake by lettuce.

3.1.3 DEVELOPMENT OF TECHNOLOGY TO CONTROL FUNCTIONAL COMPONENTS

3.1.3.1 Giving Some Stress

Ingredients of a plant are often affected by some stresses. It has been reported that some ingredients increased by the stress of drought, salinity, high temperature, low temperature, high CO_2 concentration, low oxygen, high light intensity, continuous lighting, UV irradiation, injuring leaves, exposure with leaf aldehyde (hexenal) or leaf alcohol (hexenol), low temperature of root zone, or low oxygen of root zone.

Water stress including drought and salinity is the treatment to suppress water absorption by plants by limiting irrigation or increasing the concentration of nutrient solution. Though it is thought that one of the main effect is concentrating action by low water content in the plants, the water stress also affects metabolism and water-stressed plant sometimes accumulate some kinds of substance which is called osmotic solute. The major osmotic solute is sucrose and amino acids such as proline and glutamic acid. The treatment is used for producing the tomatoes containing higher sugars. It is known that water-stressed tomatoes contain higher sugars, glutamic acid, and lycopene, and tomatoes usually contain little sucrose but water-stressed tomatoes contain sucrose. Increasing the concentration of nutrient solution, which is called salinity stress, is carried out by increasing nutrients or supplemental addition of some kinds of salts such as NaCl or $CaCl_2 \cdot 2H_2O$. It is known that organic acids increase in the method increasing nutrient concentration. Plants would absorb much K from the nutrient solution containing high concentration of K. It is thought that plants might synthesize organic acid to avoid cytoplasm alkalized by K accumulation [5].

It is known that the stress by higher temperature or lower temperature causes synthesize of some kinds of protein by activating some gene expression. An accumulation of sucrose under lower temperature is famous.

Treatments of high CO_2 or lower oxygen suppress the respiration or oxidation by making anaerobic condition and suppress the decrease of the contents of antioxidants and increase the contents of aldehydes and alcohols.

Higher light intensity or continuous lighting activates the generation of active oxygen, and then increases the contents of antioxidants such as ascorbic acid or polyphenols, for example, sesamin of sesame.

Irradiation of UV light is one of the famous stress treatments. It is known that UV irradiation increases antioxidants such as ascorbic acid and polyphenols such as anthocyanins or resveratrol. The effects are induced by the irradiation of UV-B (280–320 nm), but very little by UV-A (320–400 nm). Since UV-B irradiation causes injury of leaves, attention should be paid on how long and strong the UV irradiates to the plants.

When plants are suffered from physical stimulus or injury by insects, the plants synthesize some substances besides ethylene. One of the substances is leaf aldehyde and leaf alcohol, and these substances could increase antioxidants. These effects are enhanced by simultaneous treatment by UV-B irradiation.

It has been reported that low temperature treatments to root zone increased contents of sugars and ascorbic acid in spinach leaves and the flavonoids such as rosmarinic acid luteolin in perilla leaves [6,7]. Though it can be thought that one of the reasons is suppression of root uptake to minerals such as phosphor, there is possibility that low temperature in the root zone activates some gene expression. However, it was reported that low oxygen treatment to the root zone (no aeration to the nutrient solution) increased contents of pinitol in ice plants.

3.1.3.2 Treatments Based on Metabolic Pathway

Sometimes, the treatments for increasing some components are searched from metabolic pathway of the target components. A typical example is an oxalic acid pathway of spinach. The spinach accumulates much oxalic acid in the leaves, and the oxalic acid pathway is strongly associated with nitrate, ascorbic acid, and glucose [8]. The nitrate absorbed by plants is reduced to nitrite and then ammonium. Though the cytoplasm is alkalized with the reduction, plants synthesize some organic acids to neutralize the cytoplasm. In the case of spinach plants, oxalic acid is synthesized, and main synthetic pathway of it is the degradation of ascorbic acid. Therefore, if root absorption of nitrate is restricted, the synthesis of oxalic acid would decrease, and then, glucose and ascorbic acid which are not used for synthesis of oxalic acid would increase. The method limiting nitrate absorption by spinach plants has been put to practical use widely [9]. Restriction of plant absorption of nitrate is carried out by withdrawal of nitrate in the nutrient solution or cooling the root zone. Furthermore, since the activity of nitrite reductase, which catalyzes the reduction of nitrite to ammonium, increases with Mo, the foliar application of Mo solution could decrease nitrate content [10].

It is known that higher light intensity increases the contents of carotenoids, especially xanthophyll cycle pigments which are synthesized by degradation of β-carotene [11]. Plants have mechanisms to discard surplus light energy not used to photosynthesis. One of the mechanisms is carotenoids pathway. Therefore, carotenoids contents also could be increased under the condition limiting photosynthesis such as low temperature, low CO_2 concentration, or water stress.

Some of functional components in plants accumulate in the plants in the form of glycosides. For example, anthocyanin is a glycoside of anthocyanidin combined with glucose. The glycosides could be increased under the condition of increasing glucose content. The glucose is made from degradation of sucrose or starch, and then it combines with phosphor which is from ATP by the catalysis of hexokinase in the first step in glycolysis. Furthermore, the hexokinase needs magnesium for its activation. Therefore, the limiting glycolysis by deficit of phosphor or magnesium or low temperature could increase glucose contents and then could increase glycosides.

As described above, searching metabolic pathway of target component is one of the procedures to develop the methods of increasing it, if its metabolic pathway has already been known.

3.1.4 CONCLUSIONS AND PROSPECTS

The production of some new vegetables and functional plants other than lettuces in the plant factories will be increasing. Some herbs and ice plants have already been produced in the plant factories commercially. New vegetables, such as strawberries, tomatoes, potatoes, perilla, sesame, barley seedlings, and so on, have already tested to grow in the plant factory. Functional vegetables, ashwagandha, botan-bofu, saffron, and some medicine plants such as Korean ginseng, licorice, *Hedyotis diffusa*, *Valeriana fauriei*, and so on have been studied. The production of genetically modified plants such as *Nicotiana* plants including a kind of vaccine has also been studied. In fact, the strawberry including interferon for canine periodontal disease is produced commercially. The development of new LED with higher light intensity or specific spectra which is useful for increasing some functional components is proceeding. It will be more desired that the plants which are difficult to grow on the soil culture in open fields or high valued plants which are marketed in high price will be produced in the plant factories stably and all-year round. We hope that this chapter will help you to develop new technology to grow new plants in the plant factory.

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CHAPTER

3.2

Assessment From Food Science

Takaharu Kameoka, Atsushi Hashimoto
Graduate School of Bioresources, Mie University, Tsu, Mie, Japan

OUTLINE

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3.2.1 INTRODUCTION

Vegetables have been cultivated based on "experience and intuition" under relatively stable environmental conditions in open fields. However, climate change, such as torrential rain, heavy snowfall, and hot summers, have recently become conspicuous, and there is a need for "science based agriculture" to cultivate and manage based on the related data such as plant physiology, acquired environmental information, and tree information in addition to experience and intuition. Open field cultivation has an advantage in that the outdoor cultivation costs less than the facility cultivation when compared in the same area. However, an artificial light-type plant factory that artificially produces the cultivation environment and can plan uniformly growing agricultural crops is worthy of attention in the case of leaf vegetables that can be cultivated by artificial light based on the energy profitability.

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The history of the plant factory could be represented by three developments. The first one occurred in the mid to late 1980s, and in this time period, Daiei's biofarm and Tsukuba Science Expo's rotary lettuce production factory appeared. The second one occurred from the first half of the 1990s to the second half, and in this period, Kewpie began selling factory vegetables and a subsidy from the Ministry of Agriculture and Fishery was introduced. In the third one, which continues from 2009 to the present, a national project was started.

Meanwhile, the practical use of plant factories has accordingly progressed, and plant factory vegetables have begun to appear on our tables. However, from the standpoint of consumers, there is a demand for a typical plant factory of the market-in type that enables vegetable production with the quality desired by consumers. In the current plant factory, due to the dramatic development of computers and the improvement of the light environment represented by LED lighting, technological innovation is certainly taking place. However, in many plant factories, emphasis is placed on the control technology to ensure yield, but there are only a few systems that can provide vegetable quality. By the way, plant factories are divided into the following two types. One is the fully artificial light-type. These plant factories grow vegetables in a closed environment without the utilization of sunlight. The other is the sunlight-type plant factories which primarily depend on sunlight to grow vegetables in greenhouses, while using artificial light as an auxiliary light source and air conditioning technologies in the summer. These types of plant factories use both sunlight and artificial light in different combinations. Therefore, in this paper, we will consider the quality of vegetables to be produced in a fully artificial light-type plant factory.

3.2.2 ENVIRONMENTAL CONTROL AND VEGETABLES

Greenhouse farming is a cultivation method that allows the crops to fully demonstrate the inherent photosynthetic capacity and to allow high yields. In order to realize this concept, we carried out the environmental control of light, carbon dioxide, temperature and humidity, and culture fluid containing plant nutrients in the greenhouse under optimum conditions. It is also necessary to implement plant management that can most efficiently utilize the light energy from the sun in order to enhance the community photosynthetic capacity. Therefore, we need to develop a plant management system to control planting density and leaf area index.

Photosynthesis is the process by which green plants absorb light energy from the sun with the assistance of water and carbon dioxide and transform it into chemical energy to make (synthesize) carbohydrate (specifically glucose) and oxygen. The photosynthetic reaction depends on the photon number, regardless of the amount of energy that photons possess. In the case of red light, the same photosynthetic action is performed with an energy amount of 0.61 times that of blue light. This is why a lamp containing much red light can promote photosynthesis with less power than a lamp containing much blue light [1].

In the case of fruits and vegetables, such as tomatoes, assimilates synthesized by photosynthesis are commutated to appropriate the sites and distributed. By optimizing this series, it is possible to maximize the yield and quality of the fruit that is the object of harvesting in the tomato cultivation. What is necessary for crop cultivation aiming for a high yield is to supply a sufficient amount of carbon dioxide and water. Also, the higher light supply is one of the very important factors. Carbon is absorbed by plants during the process of photosynthesis. However, in order to maintain the life activity of plants, not only is photosynthesis carried out, but inorganic ions need to be absorbed by the plants. Plants absorb nitrogen and phosphorous which are necessary for producing proteins and nucleic acids. In addition, plants absorb elements such as calcium, sulfur, and magnesium necessary for life activity from the roots [2]. Table 3.2.1 shows the role of the major inorganic ions in the plant body.

3.2.3 CHANGES IN THE VALUE JUDGMENT OF AGRICULTURAL PRODUCTS

"Food culture power" is a concept linked to regional contributions. Specifically, the concept of "food culture power" is composed of "regional characteristics such as the local consumption and food mileage," "production method and catch method as a story, or ingenuity from harvesting to consumption," "traditionality, advanced nature, and social problem or social aspect linking with environmental problems,", and "thinking about environmental impact," and in recent years, the importance of "food culture power" has increased.

"Quality power" consists of newly added ethical quality and comprehensive taste making with the processing aspect, in addition to the original quality factor such as sensory quality, ingredient quality, and safety quality based on food science. Sensory quality consists of interior quality and appearance quality such as color, shape, size, and weight. It also has aroma, flavor, and technical effort. Ingredient quality is the requirement for nutrition and

TABLE 3.2.1 Role of Inorganic Ions in Plants

Element	Role in Plants and/or Constituents
N	Protein, enzyme, nucleic acid
P	Protein, enzyme, nucleic acid
S	Protein, nucleic acid
K	Ion regulation, promotion of protein synthesis
Ca	Ion regulation, cell wall
Mg	Chlorophyll, enzyme support
Fe	Electron mediator
Mo	Electron mediator, sulfate reduction
B	Carbohydrate translocation, cell wall
Cu	Electron mediator, enzyme
Mn	Enzyme
Zn	Chlorophyll synthesis
Cl	Chlorophyll activity

TABLE 3.2.2 Total Quality of Agricultural Products

Quality Requirements From Foreign Country	Regulations That Need to Be Dealt With
• General Quality ▪ Eating Quality Sweet, Sour, Bitter, Crisp, etc. ▪ Appearance Color, Shape, Size ▪ Others Smell, Weight, etc. • Ingredient Quality • Ethical Quality (Social Responsibility) ▪ Safety (Radioactive substance) ▪ Display ▪ Traceability ▪ Environment ▪ Human rights (Child Labor)	• Standardization of Agricultural Products (Standard, Making criteria obligatory, Enshrining into Law) ▪ Organic JAS ▪ Revisions to residue standard of agrichemical • Scientific approach to standardization of agricultural products ▪ Good Agricultural Practice (GAP) ▪ Global GAP, SQF2000, JGAP ▪ New ISO for quality control of Agricultural products ▪ ISO22000, ISO14000, ISO9000 ▪ SA8000 ▪ Guideline for Traceability ▪ Guideline for special cultivation display • Validation by third party

functionality. At the end of the 20th century, the problem of "food safety and security" appeared. This problem newly created the concept of traceability, bioterrorism, and food defense. At present, the presentation of safety quality (safety/security) is required in relation to this problem.

Ethical quality (social responsibility) is a new concept that appeared in the 21st century. For example, the acquisition of the International Standard for Working Environment Assessment SA 8000, which guarantees that children are not subjected to agricultural labor, implies that respect for human rights is required. Food display problems, traceability, and environmental issues related to food production, such as information on radioactivity, are also related to ethical quality. Furthermore, considering the quality of food, "changing the overall taste" accompanied by consumer preference that matched the times, consumption unit, container (packaging) characteristics, and environmental consideration is also an important factor. The plant factory packaging form of vegetables applies to this item. Table 3.2.2 shows the comprehensive quality of agricultural products.

3.2.4 QUALITY OF AGRICULTURAL PRODUCTS

The closer you pick the vegetables at harvest, the fresher and tastier they are. If agricultural products are limited only to vegetables, their quality is only the quality at the time the agricultural products arrive at the consumer. In other words, it is necessary to consider two kinds of qualities; i.e., the quality at the time that the agricultural products encounter the consumers and the quality at the time the consumer cooks the agricultural products. If the agricultural products are limited to leaf vegetables without ripening, the closer they are obtained at harvest, the fresher and the tastier. The fresh vegetables are quite high in nutritional value, but the quality after harvest will continue to deteriorate. Note that leaf vegetables are one item for classifying the type of vegetables. It is a generic term for vegetables for leaf use such as the Chinese cabbage, spinach, and celery. Therefore, fresh seasonal vegetables locally harvested are the most nutritious in vegetables grown in the open field, and deliciousness and nutritional value are superior to seasonal vegetables compared to the same kind of vegetables taken in other seasons. In addition, seasonal differences in nutritional value are noticeable in beta carotene and vitamin C, but mineral differences are almost unchanged. Specifically, the data on spinach vitamin C is reported to be about 70 mg at maximum in February and about 19 mg at minimum in July [3]. The biosynthetic pathway of vitamin C is activated by light. Specifically, the expression of an enzyme gene (VTC 2) that catalyzes the rate-limiting step of the D-mannose/L-galactose pathway is induced under light conditions and suppressed under dark conditions. Therefore, the amount of vitamin C also varies significantly depending on "When was it harvested in the day?", and "In what state was it preserved after harvesting?" In addition, prices are lower because seasonal vegetables are more available. Considering such circumstances, it is easy to understand that harvesting days must be included in the quality items of vegetables (leaf vegetables). However, at present, the harvesting date is hardly indicated. Furthermore, it is extremely important to maintain the quality based on the temperature and humidity management during the storage and transportation processes.

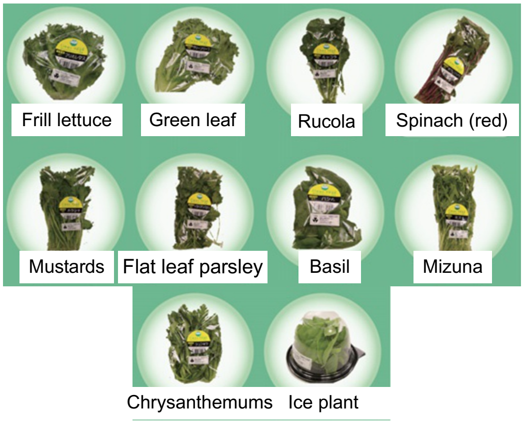
In order to image the acceptable vegetable quality by the consumer at the time of cooking, the quality deterioration rate, the optimum environmental condition to minimize the deterioration, and the optimum environmental condition for adjusting the quality are required to be scientifically clarified. In addition, it is extremely important to study the cooking recipe that makes the best use of the quality of the agricultural products (nutrition ingredients/functionality), how to convey that quality to consumers, feedback from consumers/opinions (brand and communication), and how to respond to comments. At the same time, it is indispensable to consider new methods of utilizing the ICT (Information and Communication Technology). Furthermore, implementations of the Supply Chain Management (Value Chain) covering the entire food chain based on the international certificate, scientific correspondence that considers the confidence of food related to safety and security and ethical quality (social responsibility), and providing services to consumers in terms of "the branding and quality" with a third-party verification system are urgently required.

3.2.5 VALUE OF PLANT FACTORY VEGETABLES

The value (including quality) of plant factory vegetables was discussed while taking leaf vegetables cultivated in the fully artificial light-type plant factory of the R&D center for the plant factory in Osaka Prefecture University as an example. Fig. 3.2.1 shows the vegetables cultivated in the fully artificial light-type plant factory of the R&D center for the plant factory.

Frill lettuce, which is cultivated in the fully artificial light-type plant factory of the R&D center for the plant factory in Osaka Prefecture University, has a higher antioxidant property and preservability than that cultivated in the sunlight-type plant factory. However, it is

FIG. 3.2.1 Vegetables cultivated in the fully artificial light-type plant factory of the R&D center for the plant factory.



necessary to note that it is not the result of aligning seeds, or breeding conditions (breeding period, fertilizer, etc.) [4]. Currently, lettuce is the main agricultural product of the fully artificial light-type plant factory, but it is difficult to appeal regarding taste and differentiation in terms of the quality. The amount of "TNF-α" produced by leukocyte activation by lettuce is the highest in the leafy vegetables, which shows that it has a great immunity, but consumer awareness is low [5].

In the plant factory, artificial light is used in a closed space, so it is possible to cultivate leafy vegetables completely without agricultural chemicals and without seasonality and location dependence. Therefore, plant factory vegetables generally have characteristics such as no pesticides, no washing, longlasting due to low bacterial count, less loss, a kind of deliciousness with a crunchy texture, and high functionality. Plant factory vegetables, especially leaf vegetables, are low in "value," making plant factory vegetables able to be purchased. In the supply chain, it is treated as a buffer (alternatives) when the price of vegetables from outdoor farming is rising or their quality has deteriorated due to abnormal weather. Therefore, it will be exposed to severe price/quality competition with vegetables cultivated outdoors, but it is difficult to overcome the competition because of the cost structure and quality of the plant factory vegetables [6]. Also, the quality and conditions required for vegetables are different for consumers and processing/business use. Therefore, expansion of the market is difficult with the idea of producing and selling by the cultivation method. Especially, for processing/business use, it is important to cooperate with users from the planting stage to develop plant factory vegetables and to partner with the food processing industry [7].

To overcome this situation, for consumers, it is necessary to emphasize varieties and quality different from those of vegetables produced on the farm or at other plant factories, and it is also important as how to add values such as emphasizing the strengths of their own companies and providing ads to capture the hearts of consumers. For example, since various types of cut vegetables are increasing in recent years, it is thought that considering expansion to "the sixth industry" that connects production and processing like cut vegetables is one of the ways of adding value [6].

3.2.6 VEGETABLE QUALITY DESIGN [6,8]

It is important to be thoroughly aware of the differentiation between plant factory vegetables and outdoor farming vegetables through the proprietary brand value proposal of the plant factory vegetables to consumers and users. The transmission of the goodness of the factory vegetables as a basic premise is inevitable, together with the bag-filled style in which "produced in a plant factory" and the harvest date are specified. Also, it is required to establish the structure of the market-in in its original meaning from the market side. What is important here is whether to take the concept of changing the production crops (cultivars) and cultivation methods for each purpose, such as for consumers, business use, raw materials for processed food, or whether to plan with price focus or quality emphasis. Regarding the vegetable production for business use or raw materials for processed food, it is necessary to promote the development-type deployment in collaboration with users from the development and selection stage of the varieties.

Since concepts such as safety, security, and stability are generally used for business brands, it is difficult to appeal to consumers. There are two ways to think about how to effectively work for consumers. One such proposal is a cooking recipe that assumes specific leaf vegetable use scenarios at home. Another is the presentation of the packaging style that considers purchased households. The difference in cost between outdoor farming cultivation and plant factory cultivation is significant, and cultivation at a plant factory has a current disadvantage in terms of competition conditions. For this reason, we will continue pursuing further cost reductions through improvement of the plant production technology at plant factories, as well as consideration for high added value and branding due to differentiation other than taste, such as sanitary hygiene of the harvested vegetables. Important items in terms of quality are shown in the following sections.

3.2.6.1 Nutrition Component [9]

There are the three major nutrients, such as carbohydrate, protein, and lipid, which make up the body. To adjust the health of the body, add these with vitamins and minerals and call it the Great Lipstick. Sometimes, it is called the Six Major Nutrients by adding Dietary Fiber.

3.2.6.2 Functional Component [10]

"Functional nutrition ingredient" is involved in antioxidant, immunity improvement, promotion of metabolism, etc., while supplementing the function of the five major nutrients. "Functional food" is a concept defined by the specific research "Systematic Analysis and Development of Food Function (1984–1986)" of the Ministry of Education (now Ministry of Education, Culture, Sports, Science and Technology; Japan, MEXT) for the first time in the world and refers to a food having a tertiary function among the food functions. In particular, a food ingredient involved in the bioregulatory function as a tertiary function of a food is called a functional ingredient. Plant secondary metabolic components such as polyphenols, carotenoids, isothiocyanate, and the like are representative functional ingredients since they exhibit various biomodulating functions. In addition, the functional component contains a component exhibiting a bioregulatory function among the protein-related compounds such as proteins, peptidase and amino acids, carbohydrates, such as polysaccharides, oligosaccharides, and monosaccharides, complex lipids, and highly unsaturated fatty acids.

"Food with Function Claims" that makes it easy to display the health effects and effects on health on the package has occurred since FY 2014 [11]. In addition to showing the scientific basis just by showing the function, the entry barriers are lower than "Food for Specified Health Use, TOKUHO" that needs to be examined by the national government, so manufacturers aiming to stimulate demand are entering one after another. However, issues, such as making standards for sales methods, remain [12].

In the case of processed food such as supplements, the display of functional food can be realized on the final product or on the basis of the research review of the functional involved components for the validity of the functionality. Meanwhile, in fresh food, clinical trials using the final products are required for displaying functional food. In order to display functional food, it is also necessary to identify the functional-involved components and to measure their contents and to examine the mechanism of action, which is how the reaction mechanism in the body is affected and influenced. More importantly, the functionality should be confirmed in these ways and clarified as "with evidence" and should be also ensured in fresh food, processed food, and supplements in all the production lots. At the same time, it is necessary to conduct production process control of the GMP (Good Manufacturing Practice) used for ensuring safety, to reliably confirm the raw materials and to carry out production with the secured content of the functional ingredients. At present, since there is no mechanism to raise the consumer's power while supporting consumers who seem to be the most important, this system development is urgently required. Considering the various conditions, it is expected that the "functional display food" of fresh food will be realized with leaf vegetables produced by a "completely artificial light-type plant factory."

3.2.7 VEGETABLE CULTIVATION RECIPE DEVELOPMENT

3.2.7.1 Seedling Selection [13–15]

At the large-scale plant factory of Osaka Prefecture University which was constructed in September 2014 with the aid of the Ministry of Economy, Trade and Industry "Innovation center establishment assistance program," the latest seedling sorting robot system, which judges productivity by using bioluminescence, is operating. The feature of this system is that 5000 seedlings are comprehensively diagnosed including the diagnosis of circadian rhythm in chronological order every day. The parameter set at 6000 lines per day and 5000 lines per day are selected as excellent seedlings. Seedling selection is done at the final stage of the seeding/greening process carried out in the greening room for 4 days in the order of seeding, emergence, greening, and seedling selection. Mechanization is essential in terms of continuity and reliability in order to achieve a throughput of 6000 daily. Productivity is emphasized in diagnosis, and at the present time, there is no mention of the relation between bioluminescence and quality factors such as the nutritional components and functionality of lettuce.

3.2.7.2 Cultivation Recipe [16,17]

In response to the establishment of a low potassium content lettuce cultivation method using a hydroponic culture, Aizufujikako Co., Ltd. has begun to sell low potassium lettuce in earnest for dialysis patients with kidney disease whose intake of potassium is restricted because potassium cannot be sufficiently discharged from the body. In March 2015, Aizufujikako Co., Ltd. transferred all business related to the franchise business operation to Dr. Vegetable Japan Co., Ltd. Now, Dr. Vegetable Japan Co., Ltd., manufactures low potassium vegetables and aims to spread to domestic and overseas markets. Currently, three low potassium lettuce plant factories are located in the Chiba Prefecture, in Tokyo Metropolis and in the Saitama Prefecture. Each produces 4000 heads of lettuce, 2500 heads of lettuce, and 4600 heads of lettuce per day, respectively. Another plant factory is in Kagawa Prefecture and produces 4800 heads of lettuce per day. The growing environment such as temperature, humidity and light are controlled and managed so that every factory maintains the quality defined as the “doctor vegetable brand.” In addition to wearing a clean suit and sanitary control by an air shower, metal detectors are also standardized to avoid contamination of foreign matter and to enhance safety.

At the moment, it remains in a special market, and the market size is not very large. However, following the lettuce, it became possible to cultivate spinach with a low potassium content in July 2015. Specifically, spinach can be harvested with a low potassium content while maintaining the growth of the edible part by a cultivation method which does not reduce potassium in the early stage of cultivation and does not give potassium from the middle of cultivation. It has been confirmed that this cultivation method can be applied to other leaf vegetables as well as the possibility of application to fruit vegetables. Therefore, establishing such a hydroponic cultivation method is considered to have a great significance. In addition to the close relationship between the function of inorganic ions and the health of agricultural crops, inorganic ions in vegetables play a very important role in securing food quality as a functionality. Based on plant physiology and plant pathology, cultivation recipes for each agricultural crop in which the relationships between inorganic ions and agricultural health are quantitatively arranged and that take into account the light source spectrum will be essential for the artificial light plant factory.

3.2.8 GENETICALLY MODIFIED PLANT FACTORY [18]

In the fully artificial light-type plant factory, it is possible to increase the production by thoroughly controlling the growing conditions by making raw materials and vaccines for medicines in plants using gene recombination technology [18]. Therefore, “plant pharmaceutical factory” project is being advanced. Plants can not only provide active ingredients by grinding, but can also be kept for 2 years without freezing if they are lyophilized. Also, there is an advantage that it can be grown all year without being influenced by the weather.

The plant factory of the National Institute of Advanced Industrial Science and Technology (AIST) is equipped with artificial environment functions. Temperature, humidity, CO_2 level, wind speed, and airflows in the cultivation room can be precisely controlled as desired, and almost any kind of plant can be grown. It is also equipped with dispersal prevention systems that comply with the Cartagena Protocol on Biosafety. The factory is divided into a cultivation area and a production area, so the final product can be manufactured from the plant within one building. AIST, Hokusan Co., Ltd., and the Kitasato Institute have developed and started to sell a medicine for dogs for the first time in the world in March 2014. The source of this medicine is strawberries that, thanks to genetic modification, produce a carine interferon. Genetically modified (GM) strawberries were grown in AIST's completely closed system plant factory. GM plants can be used as the raw material source for plant-derived medicines.

Herbal plants provide the ingredients of traditional Chinese medicine. However, little information about these plants has been published about the results of hydroponic cultivation in the plant factory. Many of these herbs are currently harvested only in certain regions in China and elsewhere, and many of them cannot be artificially grown. Perhaps, they can be artificially grown if the conditions of those regions can be reproduced within a factory and herbs that are many times more medicinally potent could be produced.

Production processes for new pharmaceuticals can be developed, and the new materials for herbal medicines can be cultivated. These will help to stabilize the supplies and increase the concentrations of the active ingredients. The GM plant factory has been producing some success in recent years, which will provide a significant opportunity for plant factory vegetables in the future. However, there are still many issues to be put into practical use such as technology transfer. The capability of the plant factory should be more improved to stimulate the plant biotechnology industry and to help people and animals with medical treatments.

3.2.9 CONCLUSIONS

For the tomato cultivation using sunlight-type plant factory, cultivation management including environmental control has improved productivity with the aim of matching the productivity of greenhouse farming in the Netherlands. The fact that tomato quality design is extremely difficult as it cannot control the sunlight also leads to this direction. Meanwhile, even at the artificial light-type plant factories where leaf vegetables are cultivated, the main objective is also placed on the productivity, while the quality design has been postponed because the taste of leaf vegetables mainly depends on freshness. However, from the author's point of view of "Assessment from food science," because it is targeted on leaf vegetables from the artificial light-type plant factory, the artificial light-type plant factory should develop environmental control and a cultivation management system that can design inorganic ions, functional ingredients and taste, and it should also aim for development of a new cultivation recipe.

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CHAPTER

3.3

Functional Plants

Hiromichi Itoh

Department of Agricultural Engineering and Socio-Economics, Graduate School of Agricultural Science, Kobe University, Japan

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3.3.1 INTRODUCTION

Plant factories have been constructed at 208 sites in Japan (197 sites as to fully artificial light-type and 31 sites in relation to a mixed type) as of February 2017. The number is 2.6 times the amount for previous 6 year [1]. Construction sites still have increased. However, management income and expenditure of plant factory business have not been strong. Though percentage of plant factories in deficit operation has decreased by rationalization of business and production process, the 50% of fully artificial light-type and 35% of a mixed type were in deficit in 2016. Producers recognized several issues for surplus business, such as control of pest and disease, yield stabilization, improvements of cultivation technique, and

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improvements to sales price by increasing the added value [1]. The issues are divided into two factors, one is the reduction of production cost and the other is the improvement of added value in produced plants. This section focuses on the latter factor. There would be several indices of the added value, such as freshness, color, smell, and nutritional value. Excepting the external appearance, these indices are function of food. An improvement of the functionality in produced plants would be one of effective approaches to make plant factory more profitable.

Vegetables produced in plant factories are one kind of food. Food, which have specific function, are called functional food. The functional food is defined in laws in Japan. In this section, the functional food and functional components are explained at first and then fundamentals to begin research on cultivation of medicinal plants are explained. Though medicinal plants are not food, these plants should be adequate cultivar to be produced in plant factory because medicinal plant includes specific functional components and, therefore, has higher added value than vegetables.

3.3.2 FUNCTIONAL FOOD

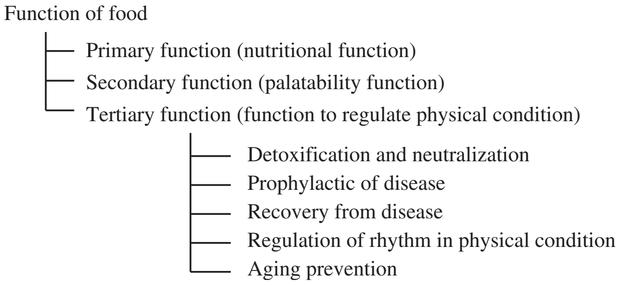
3.3.2.1 Function of Food

The term "functional food" was defined in Japan ahead of other countries. A Grant-in-Aid for Special Project Research subsidized from Ministry of Education began from 1984 [2] and three functions of food were stipulated as shown in Fig. 3.3.1. Primary function is to provide the minimum nutrients and calories necessary to sustain life. Secondary function is to give tasty feeling in relation to taste and smell. Tertiary function is to maintain physical condition including the following elements; detoxification, prophylactic of disease, recovery from disease, regulation of rhythm in physical condition, and aging prevention. Functional food was defined as food which had the tertiary function [3].

3.3.2.2 Food With Health Claims in Japan

Pharmaceutical products and food with health claims receive several regulations. Fig. 3.3.2 shows a classification of food with health claims and pharmaceutical products [4]. Pharmaceutical products, quasi-pharmaceutical products and food receive regulations of The Law on

FIG. 3.3.1 Function of food.


Function of food
Primary function (nutritional function)
Secondary function (palatability function)
Tertiary function (function to regulate physical condition)
Detoxification and neutralization
Prophylactic of disease
Recovery from disease
Regulation of rhythm in physical condition
Aging prevention

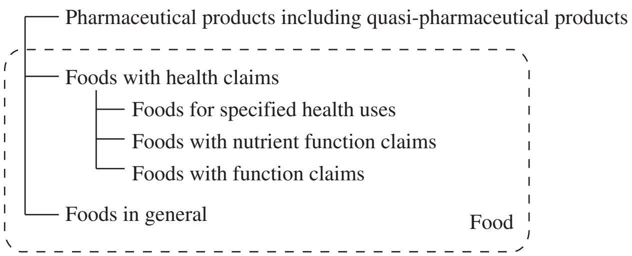

Pharmaceutical products including quasi-pharmaceutical products
Foods with health claims
Foods for specified health uses
Foods with nutrient function claims
Foods with function claims
Foods in general
Food

FIG. 3.3.2 Classification of food with health claims [4].

Securing Quality, Efficacy and Safety of Products Including Pharmaceuticals and Medical devices [5]. This law is superior to Food Sanitation Act [6,7]. Eatables and drinkables, which are taken from the mouth and don't fall under pharmaceutical products, are assigned to food. Food with health claim is divided into three categories.

Food for specified health uses (FOSHU) receive regulations of Health Promotion Act [8] and are scientifically recognized as helpful for maintaining and promoting health and are permitted to bear claims such as "Slows cholesterol absorption." The government evaluates the claimed effects and safety, and the Secretary-General of the Consumer Affairs Agency gives approval for the labeling of each food product that satisfies the requirements [4].

Food with nutrient function claims receive regulations of Food Sanitation Act and can be used to supplement or complement the daily requirement of nutrients (vitamins, minerals, etc.) which tend to be insufficient in everyday diet. Given that the food product contains certain amounts of nutrient whose function has already been substantiated by scientific evidence, it can bear a nutrient function claim prescribed by the Standards without submitting a notification to the government [4].

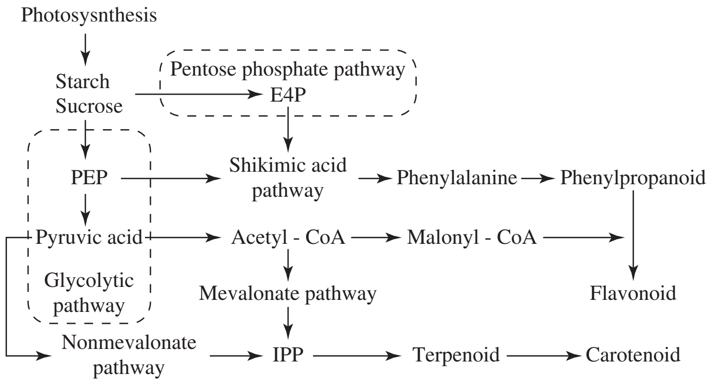
Food with function claims receive regulations of Food Labeling Act [9] and can be labeled with function claims based on scientific evidence under the food business operator's own responsibility. Information on the evidence supporting the safety and effectiveness of the product are submitted to the Secretary-General of the Consumer Affairs Agency before the product is marketed. However, unlike FOSHU, the product is not individually preapproved by the Secretary-General of the Consumer Affairs Agency [4].

The three kinds of food with health claims can label a function claim. However, food in general cannot label a function claim. Any food labeled as a nutritional supplement, a health supplement, or a nutrient controlling food fall under food in general [4].

3.3.3 NUTRIENT COMPONENT IN PLANTS

Plants biosynthesize many metabolites. Metabolites are divided into primary and secondary metabolites. Primary metabolism is a metabolic pathway to support life phenomenon and is found in common among living things. In primary metabolism, carbohydrates, amino acids, proteins, lipids, and nucleic acids are biosynthesized as primary metabolite. Secondary metabolism is a metabolic pathway to biosynthesize specific chemical compounds in particular living things. Secondary metabolites are derived from primary metabolites and have been used as medicines, perfumes, dyes, and paints. Chlorophyll, terpenoid, alkaloid, and

FIG. 3.3.3 Schematic diagram of secondary metabolism (PEP: Phosphoenolpyruvic acid, E4P: Erythrose 4−phosphate, IPP: isopentenyl pyrophosphate).



flavonoid are representative secondary metabolites [10,11]. The primary and secondary metabolisms are shown schematically in Fig. 3.3.3. Detailed pathway could be referred in a database Kyoto Encyclopedia of Genes and Genomes (http://www.kegg.jp/kegg/).

In principal for food-related business operator, all processed food and food additives, which are prepackaged, are obliged to display nutrient compositions in accordance with Food Labeling Standards [12] under the Food Labeling Act as shown in Table 3.3.1. The core nutrient compositions and other compositions are shown in Table 3.3.2. As for the vitamins, the followings are included; niacin, pantothenic acid, biotin, vitamin A, vitamin B_1, vitamin B_2, vitamin B_6, vitamin B_{12}, vitamin C, vitamin D, vitamin E, vitamin K, and Folic acid. The 12 minerals are included as follows; zinc, potassium, calcium, chromium, selenium, iron, copper, sodium, magnesium, manganese, iodine, and phosphorus.

TABLE 3.3.1 Food That is Obliged to Display Nutrient Composition

	Core Nutrient Compositions	Other Compositions
Processed food	Mandatory	Optional
Food additive	Mandatory	Optional
Perishable food	Optional	Optional

TABLE 3.3.2 Nutrient Compositions to be Labeled

	Nutrient Compositions
Core compositions	Energy, protein, total fat, carbohydrate, sodium
Other compositions (recommend)	Saturated fats, dietary fiber
Other compositions	n-3 fatty acid, n-6 fatty acid, cholesterol, sugars (monosaccharides and disaccharides), sugars (digestible carbohydrate), vitamins, minerals

Contents of nutrient compositions in principal perishable food are opened in public in Standard Tables of Food Composition in Japan [13]. According to the results of national health and nutrition examination survey in Japan [14], 35.9% of dietary fiber, 53.4% of vitamin A, 40.3% of vitamin C, 22.6% of potassium, and 16.9% of calcium are taken from vegetables. Vegetables are important resources of nutrients indispensable to maintain good health.

3.3.4 FUNCTIONAL COMPONENT IN PLANTS

Functional components have tertiary function shown in Fig. 3.3.1. Functional components include primary and secondary metabolites. Table 3.3.3 shows representative functional components included in vegetables and fruits [15]. The functions of the components could be referred in web sites, such as Information system on safety and effectiveness for health food surveyed by National Institute of Health and Nutrition in Japan [16] or Dietary Supplement Fact Sheets investigated by National Institute of Health in USA [17]. Green and yellow vegetables contain many kinds of functional components and provide the tertiary function.

Table 3.3.4 shows medicinal property of medicinal plants, which are top 10 cultivar of amount used in Japan in 2014 [18,19]. Standard of pharmaceutical products is prescribed in The Japanese Pharmacopoeia [20].

TABLE 3.3.3 Representative Functional Components

Functional Component	Typical Vegetable
Dietary fiber	Shallot, Red pepper, green pea
Polyphenol	
Apiin	Parsley, celery
Chlorogenic acid	Sweet potato, burdock, eggplant
Lactucopicrin	Lettuce, chicory
Anthocyanin	Red perilla, eggplant, watermelon
Quercetin	Onion, shallot
Rutin	Kale, spinach
isoflavone	Vicia bean, green soybean
Gingerol	Ginger
Amino acid	
Lysine	Vicia bean, green soybean, garlic, broccoli
Tryptophan	Vicia bean, green soybean, garlic, spinach
Aspartic acid	Asparagus,Tomato
Glutamic acid	Tomato, chinese cabbage
Sugars (digestible carbohydrate)	

Continued

TABLE 3.3.3 Representative FunctionalComponents—Cont'd

Functional Component	Typical Vegetable
Oligosaccharide	Burdock, onion
Xylitol	Strawberry, lettuce, spinach, cauliflower
Lipid	
Lecithin	Green soybean
Vitamin	
Cabagin (Vitamin U)	Cabbage, lettuce, celery
Ascorbic acid (Vitamin C)	Vegetables and fruits
Carotenoid	
α-Carotene, β-carotene	Carrot, spinach, broccoli, pumpkin
Lycopene	Tomato, watermelon
Capsanthin	Sweet pepper
Zeaxanthin	Spinach, mango, papaya
β-cryptoxanthin	Maize, ponkan orange, orange
Lutein	Spinach, maize
Isothiocyanate	
Allyl sulfide	Onion, welsh onion, garlic chive, garlic, Shallot
Isothiocyanic acid	Cabbage, broccoli, cauliflower
Chlorophyll	Spinach, garlic chive, sweet pepper

TABLE 3.3.4 Medicinal Plants That Were Top 10 of Amount Used in Japan in 2014 and Their Medicinal Property

Cutivar	Medicinal Property
Senna pods	Sennoside
Glycyrrhiza	Glycyrrhizic acid
Poria Sclerotium	Eburicoic acid, etc.
Peony Root	Paeoniflorin
Cinnamon Bark	Cinnamaldehyde, etc.
Koi	Maltose
Japanese Angelica Root	Ligustilide, etc.
Jujube	Oleanolic acid, etc.
Pinellia Tuber	3,4-Dihydroxybenzaldehyde, etc.
Atractylodes Lancea Rhizome	beta-Eudesmol, etc.

3.3.5 FUNDAMENTALS TO BEGIN RESEARCH ON CULTIVATION OF MEDICINAL PLANTS

3.3.5.1 The Meaning of Production at Plant Factory in Japan

The percentage of producing country in relation to total amount of crude drug used in Japan in 2014 was 10.3% from Japan, 78.8% from China, and 10.9% from other countries [18]. About 80% of crude drag was imported from China. Price of the crude drag produced in China has been unstable and has climbed because of unseasonable weather and decrease of grower and harvester of medicinal plants due to economic development in China [21]. The mean of purchase prices of crude drag, which were made in China and showed top 30 amounts used in Japan, rose by 2.4 times in 2015, comparing with the price in 2006 [22]. At the same time, China has focused on an internationalization of traditional Chinese medicine and would export crude drags to European countries. Tightness in supply of crude drags to Japan from China has been of concern. Therefore, it is inevitable to design policies to avoid a country risk. However, it would not be easy to promote the analysis of cultivation of wild cultivar and the cultivation in foreign countries [21].

The analysis of cultivation of medicinal plants can be feasible in the fully artificial light-type plant factory because climates in foreign country can be reproduced in the plant factory even in Japan. It is possible to produce high-quality and safe plants stably in plant factory, though production cost is high. On the other hand, medicinal plants have higher added value than vegetables and it is difficult to cultivate high-quality and safe plants in a field. In the relationship between plant factory and medicinal plants, the one side advantage compensates issues of the other side as shown in Fig. 3.3.4. Furthermore, there is a possibility to mass-produce medicinal plants with very high quality under artificial environments that is impossible in natural climate. Medicinal plants are suitable for production cultivar in plant factories.

3.3.5.2 Selection of Cultivar

Selection of cultivar is the first step of researches on growth control of medicinal plants in plant factory. This step is very important from a viewpoint of efficiency of the research and profitability for plant factory business. Fig. 3.3.5 shows a policy for the selection of cultivar.

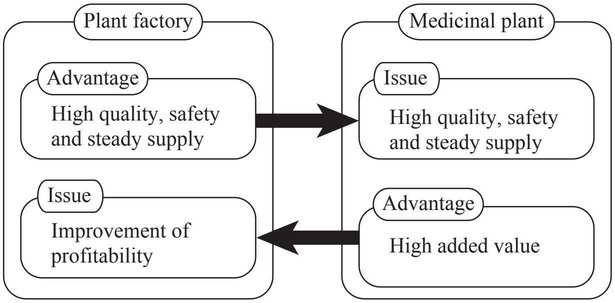

Plant factory
Advantage
High quality, safety and steady supply
Issue
Improvement of profitability
Medicinal plant
Issue
High quality, safety and steady supply
Advantage
High added value

FIG. 3.3.4 Advantage and issue of plant factory and medicinal plant.

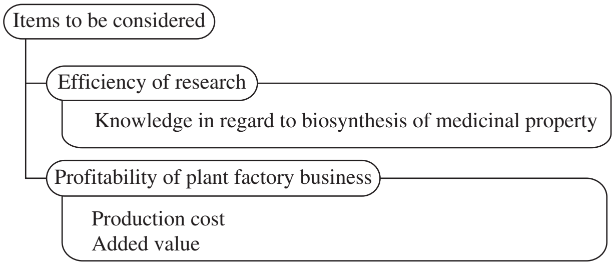

Items to be considered
Efficiency of research
Knowledge in regard to biosynthesis of medicinal property
Profitability of plant factory business
Production cost
Added value

FIG. 3.3.5 Policy to select cultivation cultivar.

Medicinal property is one of functional components and could be an index for quality of medicinal plant. Since wild medicinal plants have been used preferably as ingredients of crude drags and Kampo medicines, there is very little research result in relation to effects of environmental factors on growth and contents of medicinal property. However, if biosynthesis pathway of target medicinal property has been already clarified, enormous knowledge, which has been derived from researches on vegetables in regard to biosynthesis of metabolites, could be utilized. The vegetable information about the biosynthesis of metabolite, which is a metabolic intermediate on the pathway toward target medicinal property, is very much valuable for an elucidation of the effects of environmental factors on biosynthesis of medicinal property. The elucidation would be accelerated, if omics is available because omics comprehensively analyzes gene expressions (transcriptomics) and metabolites (metabolomics) along the biosynthesis pathway [23]. Responses of plants, such as gene expressions and metabolite productions, to environments could be elucidated in detail by omics. Therefore, the knowledge in relation to biosynthesis pathway is needed for improving research efficiency.

The selection of cultivar affects the profitability of plant factory business. Medicinal plants, which have high added value and are suitable for low cost production, should be selected. As for the added value, drug price is one of indices of added value and is received the Drug Price Standard that is calculated by Ministry of Health, Labour and Welfare [24]. Though senna pods showed the largest amount used in Japan as shown in Table 3.3.4, drug price is very cheap from 6 yen to 7 yen per gram in 2017 [24]. Considering production cost, cheap cultivar is not adequate for production in plant factory. Cultivation period is one of the important factors to make a decision of the selection. Since plants cannot be shipped during cultivation, long cultivation increases production cost. Medicinal plants, which use roots as an ingredient of crude drag, are not adequate for the production in plant factory because cultivation period becomes long in general. Though there were several researches on cultivation of medicinal plants, whose roots included medicinal properties, in the end of 1990s [25–28], these research outcomes were not adopted to plant factory industries.

3.3.5.3 Evaluation Index of Growth Control

Considering a commercial operation of plant factory, indices for evaluation of products are not only the quality, but also quantity. One of the most important quality indices is concentration of medicinal property. When the concentration is high in medicinal plants that show low dry weight under a growth control, total yield of medicinal property becomes low.

This growth control would show a low cost effectiveness and a low profitability. Therefore, content, which is the product of dry weight of a medicinal plant and concentration of medicinal property in the plant, could be an adequate evaluation index of growth control in plant factory. It is necessary to improve both the dry weight and concentration of medicinal property in order to enhance the evaluation index, which is content of medicinal property.

3.3.5.4 Concept of the Research on Growth Control of Medicinal Plants

Most medicinal properties are secondary metabolites and biosynthesis of a part of secondary metabolites is enhanced for tolerance and avoidance from environmental stresses [11]. However, stress confines growth of plant in general. Therefore, the enhancement of secondary metabolite production is inconsistent with the promotion of dry weight. Fig. 3.3.6 shows a principle for the enhancement of medicinal property content. At first, the environmental control is adopted to make photosynthesis rate increase and directly contributes to the increase of dry weight of medicinal plants through the enhancement of starch and saccharide production. In the second place, environmental control is applied to induce secondary metabolites from primary metabolites. An environmental stimulus, which would be a kind of stress for plants, is effective for the biosynthesis of secondary metabolites. Finally, improvement of both the dry weight and medicinal property concentration would enhance the content of medicinal property. Therefore, the research on growth control of medicinal plants arrives at an optimization of the balance between primary and secondary metabolites production.

3.3.5.5 Environmental Factors Used for Control of Medicinal Property Content

Environmental factors, which can impart an adequate stress to medicinal plants, have potential to control the concentration of medicinal property. The followings are environmental stresses that can be controlled in plant factory: air temperature, quantity and quality of light, moisture, osmotic pressure in root system, nutrition, pH, and wind velocity [11]. The lighting condition is an effective factor to control both the dry weight and concentration of medicinal property. The lighting condition is defined by light intensity, radiation spectrum,

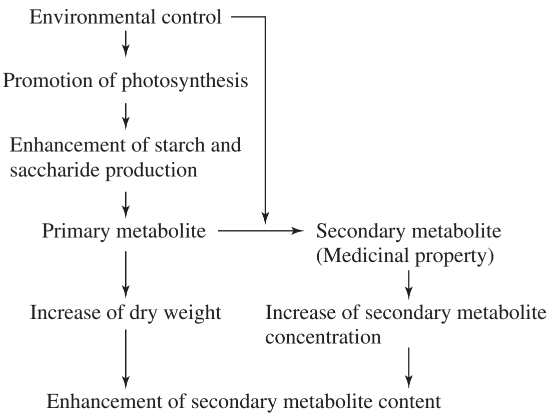

Environmental control
Promotion of photosynthesis
Enhancement of starch and saccharide production
Primary metabolite
Secondary metabolite (Medicinal property)
Increase of dry weight
Increase of secondary metabolite concentration
Enhancement of secondary metabolite content

FIG. 3.3.6 Principle to improve the content of medicinal property by environmental control.

and light-dark period. Though an increase of photosynthetically photon flux density augments dry weight, excessive intensity can be a stress for plants. According to the results of research on the effect of photon flux density and light-dark period on asperuloside content in *Hedyotis diffusa* [29], the asperuloside concentration enhanced with the increase of light period and showed sudden rise at 24 h of light period. The strong light stress caused by the long light period would enhance the biosynthesis of asperuloside, which is one of medicinal properties of *Hedyotis diffusa*. Since the dry weight also increased with the increase of light period, the asperuloside content increased when the light period was long. In this case, the variation of concentration of medicinal property was not inconsistent with that of dry weight. As for the effect of light quality, which is defined by radiation spectrum of light source, there is a research on alkaloid yields of *Catharanthus roseus* [30]. The irradiation with red light alone could be used to improve biomass production and yields of alkaloid in *Catharanthus roseus*, increasing the potential application of this plant species to the production of anticancer agents. The effect of air temperature on biosynthesis of asperuloside in *Hedyotis diffusa* has been analyzed [31]. *Hedyotis diffusa* were cultivated in a growth chamber at 20°C, 25°C, and 30°C of air temperature, which was set at the same value in both light and dark periods. When the air temperature increased, dry weight increased, but asperuloside concentration decreased on the contrary. *Hedyotis diffusa* prefers high air temperature because *Hedyotis diffusa* is naturally distributed in the subtropical and tropical zones of East Asia. The temperature at 20°C was not adequate for growth and became a stress. The increase of dry weight was inconsistent with the enhancement of biosynthesis of medicinal property. In order to solve the trade-off problem, more detailed setting of air temperature would be necessary, such as a separate setting of air temperature at light and dark periods, respectively.

3.3.6 CONCLUSIONS AND PROSPECTS

Consumers demand high quality for edible vegetables. The functionality is one of the important indices of quality and comes from functional components in vegetables. Therefore, information of food labeling should be precise and, thus, receives several regulations. In the case of medicinal plants, the function is determined by medicinal properties. In order to raise the added value of products in plant factory, further research would be necessary for the control of concentration of functional components. The knowledge in regard to the effect of environmental factors on production of functional components has not been sufficient particularly for medicinal plants. Omics would accelerate the elucidation of the effect of environmental factors on gene expression and production of metabolites along the biosynthesis pathway toward the functional component. Outcomes generated from the advanced research would be transferred to plant factory technology and would lead to construction of "needs-oriented plant production system."

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CHAPTER

3.4

Total Performance Evaluation in Plant Factory With Artificial Lighting

Wei Fang

Department of Bio-Industrial Mechatronics Engineering, National Taiwan University, Taipei, Taiwan (R.O.C.)

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3.4.1 INTRODUCTION

Plant factory with artificial lighting (PFAL) gained worldwide attention recently due to several "GloNaCal" reasons such as food safety, food security, resource (oil and fresh water) shortage, global warming, extreme weather, and steady supply. GloNaCal is a new term describing issues related not only lo*cal*ly, but *na*tionwide as well as *glo*bally. In spite of its high investment cost and operating cost, features of PFAL such as capability of controlling quantity, quality of crops, and risk and time required to grow attract people from all sectors.

The growth of crops in PFAL is normally separated into several stages with various growing density in order to make better use of resources. In between stages, the transplanting can be done manually or automatically. The environmental settings and cultural practices in different stage might be different to suit different purposes such as maximize the growth, minimize the cost, enhance the quality, etc. Those settings can be categorized into four different aspects: (1) Air: temperature, humidity, wind velocity, and CO_2 content. (2) Crop: variety of crop, duration, and growing density. (3) Light: intensity, spectral quality, and duration.

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(4) Nutrient solution: pH, EC, DO, and temperature. The performance of growth is the integrated outcome of above-mentioned governing factors.

Many researches were conducted to investigate various combination of above parameters aiming at different targets. However, lack of systematic means to describe various settings in various stages limits the spread of valuable research outcome; also, makes it difficult to duplicate the experiment and to exchange the experience.

In PFAL, cost of electricity occupied more than 30% in operating costs and the cost on lighting equipment (light source, power supply, reflector, etc.) also occupied a great deal in total fixed costs. In general, artificial light source, air conditioner, and pump are three major equipments that required electricity in a PFAL. When the COP of the air conditioner nears three, the electricity consumption of light source is roughly 70%–75% of the total. How to reach high efficiency in using all kind of resource is of great concern in the research of PFAL [1].

There are various types of artificial light such as fluorescent lamp, LED, CCFL, HEFL, etc. Same type of lamp from different sources might have various spectral qualities. Means to evaluate the overall performance of lamps in term of lighting efficiency and quantum / degree yield are valuable for the selection of proper light source and crop.

The concept of LUE_d (Light energy Use Efficiency) and PUE_p (Photosynthetic photon Use Efficiency) are not new. LUE and PUE are calculated based on the dry weight of the biomass produced and the photosynthetic rate of the plant, respectively. Goto [2] suggested that by adding one mole of photons lead to an increase of 0.4 g of dry mass for lettuce and the chemical energy of one unit of dry mass is around $20\,\mathrm{kJ\,g^{-1}}$. Due to the average energy of 1 mol of photons (visible light) of about 250 kJ, the LUE_d is around $0.4 \times 20/250$ that is 0.032 [3,4].

The LUE and PUE approaches only deal with the instance of measurement not for the entire growth period. Such theoretical approach is of great important to gain fundamental knowledge; however, one can't use the information to link with the real world situation. For example, the dry weight information can't derive fresh weight information if the water content of the plant is unknown. Also, light energy used in LUE only counts the photons that were absorbed by the plant. Such information can't lead to the electricity cost or energy consumed by the light source. Real world situation involved revenue and cost. The revenue related to fresh weight of plants and market price per unit fresh weight. The cost related to the breakdown of all details such as depreciation of the initial investment, the energy consumption, the labor, raw material used, packaging, shipping/handling, marketing, and many more.

If all inputs are accounted for, total factor productivity (TFP) can be taken as a measure of an economy's long-term technological change or technological dynamism. Borrowing the concept of TFP in economics, a total performance evaluation (TPE) method of PFALs was developed [5].

3.4.2 DESCRIPTION OF TPE METHODS

The TPE method composed of two groups of indicators. The first group has one indicator, which is QE ratio. QE ratio deals with hardware only. Prior to performing any cultural practices, upon the installation of artificial light on top of each layer of growing area, the QE ratio can be calculated after knowing the power consumption (in watts) directly related to light sources, power converters, starters (if any), etc. and the measurement of average PPFD (in $\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$) on top of the given growing area (A, in m^2). The PPF (in $\mu\text{mol}\,\text{s}^{-1}$) value can be derived by multiplying values of PPFD and A as shown in Eq. (3.4.1a).

Factors affecting the average PPFD value include the light source, usage of reflectors, reflectivity of reflectors, and the mounting distance from the lamp to the growing area. For example, reflectors may be installed on top of the lamps, and/or at two sides and/or four sides of the lamps. For the cool light source such as LED, the distance can be as small as 10 cm and, for fluorescent lamp, the mounting distance normally may be bigger than 20 cm.

The total power consumption (TP, in watts) to cover the entire growing area can be calculated by knowing the value per tube or panel (P) times number of tubes or panels (n) used to cover the unit growing area as shown in Eq. (3.4.1b). The value of QE ratio can be derived by dividing PPF with TP as shown in Eq. (3.4.1c).

$$\text{PPF} = \text{PPFD} \times A \tag{3.4.1a}$$

$$\text{TP} = P \times n \tag{3.4.1b}$$

$$\text{QE ratio} = \frac{\text{PPF}}{\text{TP}} \tag{3.4.1c}$$

PY, DY, and overall QE ratio calculation

In the second group, three indicators were defined; they are: DY, PY, and overall QE ratio. The first group deals with hardware only, and the second group deals with all factors related to hardware and all stages of the cultural practices in PFAL.

The second group of indicators deals with fresh weight of biomass instead of dry weight as the base for calculation, for the sale of the produces is based on fresh mass, thus the revenue of the business can be calculated if the unit price is given. Also, when the cost in using the artificial light is of interests, the power consumed in term of kWh (degree) is of great concern. One mole of photons (visible light) is about 250 kJ and is important to know; however, how many degree (kWh = 3600 kJ) of electricity energy provides 1 mole of photons and generate how many grams of fresh produce is a practical question that needs to be answered.

Daily light integral (DLI, in $\text{mol}\,\text{m}^{-2}\text{day}^{-1}$) of various stages can be calculated using values of PPFD (in $\mu\text{mol}\,\text{m}^{-2}\text{s}^{-1}$) and L (duration of light period per day, in $\text{h}\,\text{day}^{-1}$) as shown in Eq. (3.4.2a). Total light integral of each stage (i, from 1 to 3 or more), denoted TLI(i) (in $\text{mol}\,\text{m}^{-2}$), can be calculated as shown in Eq. (3.4.2b), where $D(i)$ is the duration of days in stage i.

$$\text{DLI}(i) = \text{PPFD}(i) \times L(i) \times \frac{3.6}{100} \tag{3.4.2a}$$

$$\text{TLI}(i) = \text{DLI}(i) \times D(i) \tag{3.4.2b}$$

$$\text{oTLI} = \sum \left(\frac{\text{TLI}(i)}{d(i)} \right) \tag{3.4.2c}$$

DLI and TLI are area-specific parameters. They are values associated with unit area, i.e., square meter. However, in different stages (i), crop grow in different density, denoted as

$d(i)$, in term of number of plants per square meter ($\text{plt}\,\text{m}^{-2}$). Even in the same stage, different crop might have different density as well. The term oTLI (in $\text{mol}\,\text{plt}^{-1}$) was defined as shown in Eq. (3.4.2c), converting the per area value into per plant value.

Similar approach can be used to calculate power consumption throughout entire growth stages both per area basis Eqs. (3.4.3a), (3.4.3b) and per plant basis Eq. (3.4.3c). As shown in Eq. (3.4.3a), $W(i)$ is the power consumption (in Watts) of artificial light source per unit growth area in stage i and $A(i)$ is the value of unit growth area in square meters for stage i. The unit growth area mentioned here can be one square meter or any growing layer with given value of area. DPI (daily power integral) is in $\text{deg}\,\text{m}^{-2}\text{day}^{-1}$, TPI is in $\text{deg}\,\text{m}^{-2}$, and oTPI is in $\text{deg}\,\text{plt}^{-1}$.

$$DPI(i) = \frac{W(i) \times L(i)}{A(i) \times 1000} \tag{3.4.3a}$$

$$TPI(i) = DPI(i) \times D(i) \tag{3.4.3b}$$

$$oTPI = \sum \left(\frac{TPI(i)}{d(i)} \right) \tag{3.4.3c}$$

Photon yield (PY, in $\text{g}\,\text{mol}^{-1}$) and degree yield ($DY$, in $\text{g}\,\text{deg.}^{-1}$) in term of fresh weight (FW, in $\text{g}\,\text{plt}^{-1}$) per oTLI (in $\text{mol}\,\text{plt}^{-1}$) and per oTPI (in $\text{deg}\,\text{plt}^{-1}$) were defined, as shown in Eqs. (3.4.4a), (3.4.4b), respectively. Both terms can be used to describe the performance of crop in converting light energy to biomass under given conditions.

$$\text{PY} = \frac{\text{FW}}{\text{oTLI}} \tag{3.4.4a}$$

$$\text{DY} = \frac{\text{FW}}{\text{oTPI}} \tag{3.4.4b}$$

$$\text{Overall QE ratio} = \frac{\text{DY}}{\text{PY}} = \frac{\text{oTLI}}{\text{oTPI}} \tag{3.4.4c}$$

Eqs. (3.4.4a)–(3.4.4c) provides a straightforward method of finding the best treatment among complicated situations when fresh weight of produce is of great concern. Some applications are:

1. Values of converting factor among oTLI and oTPI reveal effectiveness of light source converting energy to quantum. The best light source combination throughout growth stages most suitable to grow specific crop has the highest value among treatments.
2. Values of PY or DY for same crop under various light sources with same PPFD or same degree of energy consumption can be used to identify the best light source (same type with various spectra or various types) for the specific crop.
3. Values of PY or DY for same crop under same light sources with various PPFD or various degree of energy consumption can be used to identify the best light intensity or the best amount of electric energy consumed for the specific crop and light source.
4. Values of PY or DY for various crops under same conditions can be used to identify the best crop for the given condition from the photon use efficiency or degree of electric energy use efficiency point of view.

5. Value of DY can be converted to dollar basis when utility fee per degree is given. Thus, the electricity cost of providing light per gram of fresh weight and how much fresh weight can be produced per unit cost can be determined. However, the utility fee is highly site-dependent.
6. Both PY and DY values can be served as indicators of self-awareness or for comparison among competitors. The values can be in different form. For example, assuming DY equals 100 g fresh lettuce per degree, it also means it required 10° of electricity to produce 1 kg of fresh lettuce. For leaf lettuce production in PFAL, to produce 1 kg of fresh lettuce, 10° electricity consumption is a good benchmark. Lower the value, the best. At present, 6–8 is possible. If the value is bigger than 15, it means improvement is needed. But it doesn't tell which direction to improve.

3.4.3 CASE EXAMPLES

Installation of artificial light in different PFALs of Taiwan was used as example to introduce the concept and calculation of QE ratio. The QE ratio is an index considering light source selected and arrangement of reflectors, etc. There are 14 treatments as shown in the first column of Table 3.4.1; among these treatments, there are 9 treatments with LED tubes, 4 with LED panels, and 1 with fluorescent tubes. The first row shows the usage of 6 LED tubes with each one at 1.8 m long. Other LED tubes are at 1.2 m in length, required 9 tubes to cover 2.16 m^2 of growth area. In the last column is the QE ratio, in μmol per Joule, of all treatments.

TABLE 3.4.1 List of *QE* Ratio Calculation for 14 Layers of Growing Benches Having Different Light Source and Arrangement

Light Source	No. of Tubes or Panels	*PPFD* (μmol m^{-2} s^{-1})	*PPF* (μmol s^{-1})	Total Power consumption *W* (J s^{-1})	*QE* ratio (μmol J^{-1})
S_CW1.8	6 tubes	334.9	723.4	173	4.2
T_V	9 tubes	281.6	608.4	195	3.1
H_CW	9 tubes	273.9	73.9	212	3.1
T_A	9 tubes	225.8	487.8	189	2.6
E_CW	9 tubes	263.8	569.8	228	2.5
T_A	12 panels	411.5	888.9	432	2.1
T_N	9 tubes	186.7	403.2	196	2.1
E_WW	9 tubes	210.8	455.3	229	2.0
T_N	12 panels	378.4	809.6	428	1.9
T_M	9 tubes	168.0	326.9	193	1.9
T_M	12 panels	387.3	836.5	442	1.9
T_Y	9 tubes	168.3	363.5	188	1.9

Continued

TABLE 3.4.1 List of *QE* Ratio Calculation for 14 Layers of Growing Benches Having Different Light Source andArrangement—Cont'd

Light Source	No. of Tubes or Panels	*PPFD* (μmol m^{-2} s^{-1})	*PPF* (μmol s^{-1})	Total Power consumption *W* (J s^{-1})	*QE* ratio (μmol J^{-1})
S_R	12 panels	291.0	628.6	334	1.9
T5FL_CW	9 tubes	250.0	540	283	1.9

Note 1. *PPFD* were average value measured at 10 cm distance under LED tubes or panels and measured at 20 cm under fluorescent lamps
Note 2: Reflectors with 95% reflectivity were installed on top of 9 LEDs and 1 T5FL tubes. No reflectors were installed on top of 4 LED panels (rows with grey background).
Note 3: $PPF = PPFD \times$ Growing area, where growing area is 2.16 m^2.

The values range from 1.9 to 4.2. The higher the value, the more the photons reach the growing area per joule of energy consumed by the light source. Upon the installation of the light source on top of growing area, the QE ratio can reveal information on competiveness before growing any plants.

Growth conditions of cases in different PFALs of Taiwan were used as examples to introduce the steps in calculating the PY and DY. Shown in Tables 3.4.2 and 3.4.3 are steps of calculating oTLI and oTPI. The ratio of these two values (overall QE ratio) indicates the overall conversion efficiency of the light source throughout growing stages. The value of oTLI vs. oTPI is in mol per degree which indicates the number of "mol" of quantum provided by every

TABLE 3.4.2 Example in Calculating *oTLI* Based on Eqs. (3.4.2a)–(3.4.2c)

I	μmol m^{-2} s^{-1} *PPFD*(*i*)	h day^{-1} *L*(*i*)	Days *D*(*i*)	mol m^{-2}day^{-1} *DLI*(*i*)	mol m^{-2} *TLI*(*i*)	plt m^{-2} *d*(*i*)	mol plt^{-1} *oTLI*(*i*)
Stage 1	180	24	10	15.55	155.52	750	0.207
Stage 2	150	12	4	6.48	25.92	533	0.049
Stage 3	150	12	14	6.48	90.72	67	1.361
oTLI = 1.617							

Adapted from Fang W: Quantification of performance in plant factory. In: Technology advances in protected horticulture-proceedings of 2013 the 3rd high-level international forum on protected horticulture. Shouguang, China; 2013, pp. 64–71.

TABLE 3.4.3 Example in Calculating *oTPI* Based on Eqs. (3.4.3a)–(3.4.3c)

Stage No.	No. Lamps/layer	Watt Power/lamp	Watt/layer *W*′(*i*)	Duration h/day × days	deg/layer *TPI*′(*i*)	plts/layer *d*′(*i*)	deg plt^{-1} *oTPI*′(*i*)
1	3	30	90	240	21.6	540	0.040
2	3	30	90	48	4.32	384	0.011
3	3	30	90	168	15.12	48	0.315
oTPI = 0.366							

Adapted from Fang W: Quantification of performance in plant factory, In: Technology advances in protected horticulture-proceedings of 2013 the 3rd high-level international forum on protected horticulture. Shouguang, China; 2013, pp. 64–71.

TABLE 3.4.4 Example of Calculating Photon Yield (PY) and Degree Yield (DY) and Related Cost

Average Fresh Weight	***FW***	**50**	**g plt^{-1}**
Utility fee	*UF*	3	NT\$ deg^{-1}
Overall total light integral	*oTLI*	1.617	mol plt^{-1}
Overall total power integral	*oTPI*	0.366	deg plt^{-1}
Converting factor	$oTLI/oTPI$ or DY/PY	4.414	mol deg^{-1}
Cost per mole of quantum	$UF \times oTPI/oTLI$	0.68	NT\$ mol^{-1}
Degree yield	$DY = FW/oTPI$	136.5	g deg^{-1}
Fresh yield per NT\$	DY/UF	45.51	g NT\$$^{-1}$
Photon yield	$PY = FW/oTLI$	30.93	g mol^{-1}

Adapted from Fang W: Quantification of performance in plant factory. In: Technology advances in protected horticulture-proceedings of 2013 the 3rd high-level international forum on protected horticulture. Shouguang, China; 2013, pp. 64–71.

degree of power consumed by the light source. In this specific case, T5 fluorescent lamps were used and the value is 1.617/0.366 equals 4.414 mol deg^{-1} as shown in the fifth row of Table 3.4.4.

Table 3.4.4 shows more in-depth information with two more given data, including the utility fee (3 NT$ per degree) and the average fresh weight of the leafy greens (50 g plt^{-1}) produced using protocols shown in Tables 3.4.1 and 3.4.2. The plants were grown for 28 days, sum of $D(i)$, with low light intensity (150~180 PPFD) as shown in Table 3.4.2.

The PY value shown in the last row of Table 3.4.3 represents how efficiently the photons were used by the crop. For this specific crop, almost 31 g of fresh weight can be produced per mole of quantum provided. The PY values of various crops under same growth conditions can be compared and the type with highest PY value is the most efficient crop.

The DY value can be linked to cost if the utility fee (UF) is given. As shown in the third row from the bottom of Table 3.4.4, DY value is 136 g per degree of power consumption and value of DY/UF shows that each NT$ spent in providing light can produce 45 g of fresh produce.

Data shown in Tables 3.4.5a and 3.4.5b and 3.4.6 were compiled from PFAL company in Taiwan. Values related to oTPI and oTLI were shown in Table 3.4.5a and 3.4.5b. As shown

TABLE 3.4.5A Values Related to oTPI Calculation With Three Treatments in Stage 3

Stage No.	**Treatments**	**h/day** $L(i)$	**days** $D(i)$	**m^2/layer** $A(i)$	**plts/layer** $d'(i)$	**Lamp/layer** $n(i)$	**W/layer** $W(i)$	**deg plt^{-1}** $oTPI(i)$	**Stage 1–3** $oTPI$
1	A,B,C	24	**6**	0.84	600	**3**	60	0.014	–
2	A,B,C	24	**7**	0.84	600	**5**	100	0.028	–
3a	A	**18**	21	1.4	49	**6**	120	0.926	0.97
3b	B	**16**	21	1.4	49	**8**	160	1.097	1.14
3c	C	**16**	21	1.4	49	**10**	200	1.371	1.41

Modified from Fang W: Quantification of performance in plant factory. In: Technology advances in protected horticulture-proceedings of 2013 the 3rd high-level international forum on protected horticulture. Shouguang, China; 2013, pp. 64–71.

TABLE 3.4.5B Values Related to oTLI Calculation With Three Treatments in Stage 3

Stage No.	Treatments	h/day *L*(*i*)	days *D*(*i*)	*PPFD*(*i*)	mol m^{-2} *DLI*(*i*)	μmol m^{-2} *TLI*(*i*)	plt m^{-2} *d*(*i*)	mol plt^{-1} *oTLI*(*i*)	Stage 1–3 *oTLI*
1	A,B,C	24	**6**	90	7.78	**46.7**	714	0.065	–
2	A,B,C	24	**7**	110	9.5	**66.5**	714	0.093	–
3a	A	**18**	21	120	7.78	**163.3**	35	4.67	4.83
3b	B	**16**	21	160	9.22	**193.5**	35	5.53	5.69
3c	C	**16**	21	200	11.52	**241.9**	35	6.91	7.07

Adapted from Fang W: Quantification of performance in plant factory. In: Technology advances in protected horticulture-proceedings of 2013 the 3rd high-level international forum on protected horticulture. Shouguang, China; 2013, pp. 64–71.

TABLE 3.4.6 Quantitative Comparison on Various Treatments in Growing Same Crop

Treatments	A	B	C	X
Days from seeding to harvest	34	34	34	28
FW (in g plt^{-1})	64.3	86.8	98	50
oTPI (in deg plt^{-1})	0.97	1.14	1.41	0.366
DY (in g deg^{-1})	66.42	76.17	69.32	136.5
DY/*UF* (in g $NT\$^{-1}$)	22.14	25.39	23.11	45.51
oTLI (in mol plt^{-1})	4.83	5.69	7.07	1.617
PY (in g mol^{-1})	13.3	15.3	13.9	30.9
Overall *QE* ratio (in mol deg^{-1})	4.99	4.98	4.99	4.42

Note 1. UF (Utility Fee) is 3 NT$.per degree of electricity.
Note 2. Values in the last column were from Tables 3.4.2 and 3.4.4.
Adapted from Fang W: Quantification of performance in plant factory. In: Technology advances in protected horticulture-proceedings of 2013 the 3rd high-level international forum on protected horticulture. Shouguang, China; 2013, pp. 64–71.

in Table 3.4.5a and 3.4.5b, differences in stage 1 and 2 are on the number of LED lamps used and the duration of days of the stage. The differences among three treatments were mainly on the intensity of light (number of lamps used) and duration of light period per day in stage 3.

Table 3.4.6 shows experimental and calculated results for further explanation on methods developed. Data under treatments A, B, C are from Table 3.4.5a and 3.4.5b and data under treatment X from Tables 3.4.2–3.4.4. In spite of great differences among settings of the experimental conditions, as shown in Table 3.4.6, effects of treatments can be compared easily in terms of values of oTLI, oTPI, PY, DY, DY/UF, and overall QE ratios. These terms are generic and can be used in various combinations of conditions, even for various types of crops. The last row shows overall QE ratios. Treatments A, B, C using same LEDs led to same value at 4.99 and treatment X used fluorescent lamp and led to a lower value of 4.42.

Table 3.4.7 shows the quantitative evaluation of four LED panels and two types of lettuce using PY and DY. From the values listed under overall QE ratio, it is clear to know that LED2 make the best use of electric energy. From the relative values, one can easily tell that LED2 generates 2.35 times of photons compared with LED1 consuming same degree of electricity.

TABLE 3.4.7 Quantitative Evaluation of 4 LED Panels and 2 Types of Lettuce Using *PY* and *DY*

	Lettuce 1		**Lettuce 2**		**Overall *QE* ratio**	
	***PY* (g mol^{-1})**	***DY* (g deg^{-1})**	***PY* (g mol^{-1})**	***DY* (g deg^{-1})**	**(mol deg^{-1})**	**Relative values**
LED1	32.2	44.2	18.5	25.3	1.4	1
LED2	31.1	101.2	22.0	71.6	3.3	2.35
LED3	34.4	67.0	20.7	40.4	1.9	1.35
LED4	32.0	74.8	20.1	46.9	2.3	1.64
Average	32	72	20	46		

The last row shows lettuce 1 generate 60% more biomass under same amount of photons by comparing average PY values and generate 56% more biomass under same amount of electric energy by comparing average DY values.

As shown in Table 3.4.8, LED2 provides the largest PPFD value as shown in the second column from the left end. However, it is also the most expensive as shown in the second column from the right end. Moreover, it has the lowest converting efficiency as listed under the column with "mol J^{-1}" as the heading. With such information appeared, one might conclude that LED2 is the worst and LED1 is the best among three panels. However, if market price is available, the performance-cost (PC) comparison on three LED panels as shown in the last column reveals that LED2 has the lowest PC value and indicated that it might be the best choice among three options. It will be very much interesting to know the PY and DY of the three if the fresh weights of the produces harvested using these panels are available. The values imply the bulk effect of spectrum and other factors not mentioned.

Table 3.4.9 shows the effects of R/B ratio of LED spectrum on the generation of anthocyanin by red leaf lettuce. The focus includes not only the fresh weight, but also the phytochemical produced. As shown in the table, treatment 1.2B has the least intensity and duration of blue light and leads to highest fresh weight, but the least amount of anthocyanin. Treatment 4.8B has the highest overall QE ratio, but the poorest production of fresh weight and anthocyanin. Looks like the treatment 1.8B is the best among treatments. It produces highest amount of anthocyanin and only scarify a little fresh weight.

TABLE 3.4.8 Cost Performance of LED Panels

	PPFD	***V***	***A***	***W***	**µmol s^{-1}**	**mol J^{-1}**	**NT$/panel**	**NT$/(mol s^{-1})**
LED1	135.9	48	0.45	21.6	16.31	0.76	1200	73.6
LED2	345.3	48	1.34	64.32	41.44	0.64	1750	42.2
LED3	153.7	48	0.55	26.4	18.44	0.70	1350	73.2

Note 1. *PPFD* in µmol m^{-2} s^{-1}, measured at 15 cm distance.
Note 2. Area illuminated by the LED panel is 0.12 m^2.
Adapted from Fang W: Quantification of performance in plant factory. In: Technology advances in protected horticulture-proceedings of 2013 the 3rd high-level international forum on protected horticulture. Shouguang, China; 2013. p. 64–71.

TABLE 3.4.9 Effects of R/B Ratio on *DY* and *PY* of Red Leaf Lettuce Focusing on Anthocyanin

Light quality treatments[a]	DY (gFW deg^{-1})	DY_A (mg_anthocyanin deg^{-1})	PY (gFW mol^{-1})	PY_A (mg_anthocyanin mol^{-1})	Overall QE ratio (mol deg^{-1})
4.8B	20.20 d	0.90 d	6.27 d	0.28 d	3.22 a
3.0B	31.98 c	1.16 c	10.17 c	0.37 c	3.14 b
2.4B	38.67 b	1.45 b	12.87 b	0.48 b	3.00 c
1.8B	36.63 b	1.63 a	12.73 b	0.57 a	2.88 d
1.2B	43.65 a	1.00 b	15.72 a	0.36 c	2.76 e

[a] *Different light quality with different weeks, 4.8B = 2R8B × 6 weeks (0.8 × 6 = 4.8), 3.0B = 8R2B × 3 weeks +2R8B × 3 weeks (0.2 × 3 + 0.8 × 3 = 3.0), 2.4B = 8R2B × 4 weeks + 2R8B × 2 weeks (0.2 × 4 + 0.8 × 2 = 2.4), 1.8B = 8R2B × 5 weeks + 2R8B × 1 week (0.2 × 5 + 0.8 × 1 = 1.8), 1.2B = 8R2B × 6 weeks (0.2 × 6 = 1.2).*

Adapted from H.Y. Chung, M.Y. Chang, C.C. Wu, W. Fang, Use of quantitative Indicators to evaluate light recipe for red leaf lettuce cultivation in plant factory (to be published), 2018.

3.4.4 CONCLUSION

A systematic quantitative method was developed for the evaluation of various treatments in the overall stage-wise production of crops in PFAL.

With the given conditions of light source and cultural condition in various stages, overall performance of values in "photon" basis such as oTLI and PY and values in "degree" basis such as oTPI and DY can be derived. Values in "degree" basis can be further converted into cost basis with given utility fee information. Converting factor among oTLI and oTPI or among DY and PY is also termed overall QE ratio. This ratio reveals effectiveness of light source converting energy to quantum from sowing to harvest. However, the highest overall QE ratio does not always lead to highest DY or PY, for the ratio only involved with partial information of the hardware and doesn't include spectral of light and all others related to crops, nutrients, and environmental factors.

The beauty of PFAL is to allow self-learning with various hardware, crops, nutrients, and environmental factors. Systematic approach in finding the best protocol is of vital importance. The usage of the total performance evaluation (TPE) method developed can be very generic and can serve various purposes depending on the treatments designed. By comparing PY or DY values among treatments, the best protocol related to treatments can be identified no matter the interests in hardware such as type of light source, spectral of light, etc., in software such as settings of parameters, in types of crops to grow, recipes of nutrients, or in combinations of above. In PFAL, the fresh weight of produce or phytochemicals is the overall result of all inputs. DY, PY, and overall QE ratio can serve as technological change or technological dynamism. Higher values represent the progress toward improvement. One might not find the optimum protocol, but surely can find better solution and get improved day after day by practicing TPE method introduced checking values of these indicators.

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PART II

NEW SCIENCE AND TECHNOLOGIES FOR LOW COST PRODUCTION AND IT CONTROL SYSTEMS

CHAPTER

4.1

Development of Efficient Production System

Kenji Nakamura
Environment Monitoring Dept., ESPECMIC Corp., Neyagawa, Japan

OUTLINE

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4.1.1 INTRODUCTION

The influence of abnormal weather frequently occurring in various parts of the earth today is a big threat to the production of stable agricultural products. We are faced with a problem of how to produce and supply agricultural products. As one means of solving the problem, the plant factory is not only limited to Japan, efforts for development are being conducted all over the world. There is a feeling that industry in the plant factory has been activated by entering of many companies from variety of businesses, which produce vegetables and supply the system in the plant factory. The plant factory, on the basis of preceding companies and research achievements, is focused on engagement with improving added value using multistaging and LED lighting. Although the focusing as above-mentioned is important, large production scale, automation, and labor-saving will become more important in the future in order to

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become a sustainable industry. We would like to consider automation and labor-saving in the plant factory which we have approached and the effect of the automation and the labor-saving on labor's work and employment.

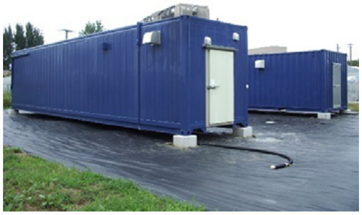

FIG. 4.1.1 Container type plant factory.

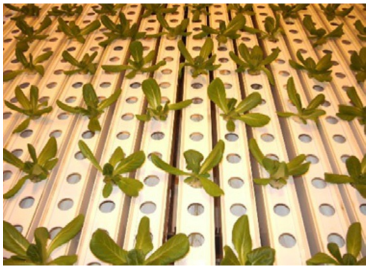

FIG. 4.1.2 One dimension spacing.

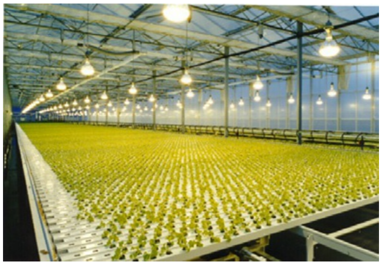

FIG. 4.1.3 Sunlight type plant factory.

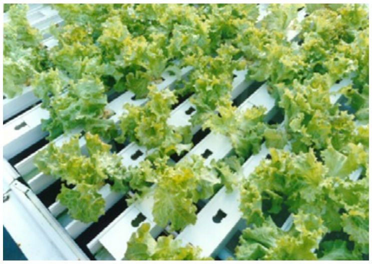

FIG. 4.1.4 Two dimensions spacing.

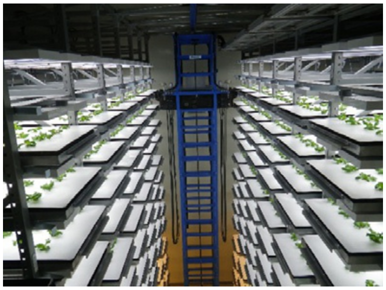

FIG. 4.1.5 Multistage type plant factory.

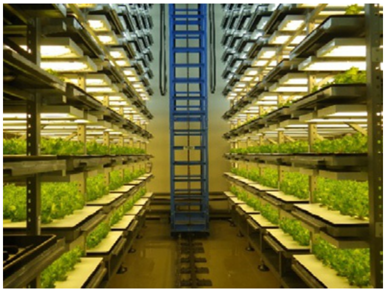

FIG. 4.1.6 Three dimensions spacing.

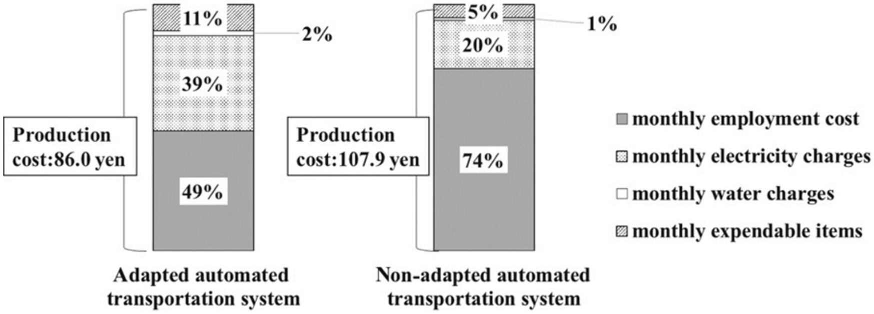

FIG. 4.1.7 Production cost rate of lettuce between adapted (left) and nonadapted (right) automated transportation systems (Depreciation is not included. Monthly electricity charges, water charges, and expendable items of the nonadapted automated transportation system are one third of those of the adapted automated transportation system).

4.1.2 DEVELOPMENT OF FLATTED SPACING SYSTEM

In container type plant factory, we developed automated spacing system, which increases the space depending on size of vegetables, for productivity improvement through effective use of flat space. It was substantiated that it is possible to improve the productivity about two times as compared with average DFT (Deep flow technique) hydroponic system. Afterward, we developed automated spacing system which automated process from planting to harvest through developing large scale of spacing system in sunlight type plant factory. In this system, we designed the process in that the labor picks up the seedling and plants into the planting hole of incoming column. We think that planting by people is better suited than machine, because the planting is important to control growth of vegetable. In the development at this time, we achieved 3D spacing through designing automated process about not only increasing space of column, but increasing space between vegetables in the columns. Therefore, we could further enhance productivity and yield.

4.1.3 DEVELOPMENT OF AUTOMATED SPACING SYSTEM

The flat type automated spacing system, which is mentioned above, was focused on improving productivity of vegetable and labor-saving through effective use of flatted space. And sterically multistaged cultivation is performed using fluorescent light and LED as a main artificial light recently. However, most examples are multiple tiered of traditional DFT and NFT system. There are few examples based on automation and carrier device. A tridimensional automated transportation system, which is made by ESPECMIC Corp., in the R&D center for plant factory in Osaka Prefecture University, is not only to use effectively small space, but to achieve that setting number of cultivation stages of shelves for cultivation period of cultivation items and increasing height direction spacing depending on growth of vegetable. In this process, we developed NFT type cultivation trays and planting panels using vacuum plastics molding technology. It is a cultivation flow in which trays and panels are going down every day and vegetables are harvested when trays and panels are at the bottom stage.

4.1.4 AUTOMATION, LABOR-SAVING, AND EMPLOYMENT

In Netherlands, stabilized management is achieved through hiring of low-wage foreign worker and labor-saving by automation in large-scale protected horticulture facilities which used moving-bench. On the other hand, in Japan, plant factory has received a lot of attention because of expectation for new industry and job creation in rural areas. Therefore, more plant factories should take precedence job creation in area than introduction of automated system that requires a lot of money. To overcome cost competitiveness of the plant factory, reduction of production cost in plant factory through the large scale, automation, and labor-saving is essential to increase competitiveness, although job creation by plant factory is important. And, development of the plant factory facilities which keep balance between job security and automation and labor-saving is also expected.

4.1.5 REVIEW OF PRODUCTIVITY ENHANCEMENT BY AUTOMATED TRANSPORTING SYSTEMS

Production efficiency of an adapted automated transporting system was compared with a nonadapted automated transportation system in plant factories.

In the adapted automated transportation device plant factory, 252 heads of lettuces were harvested every day, with the potential to harvest 92,160 heads of lettuces per year (360 harvests). In a non adapted automated transportation device plant factory, the maximum level of cultivation shelves is four due to efficiency and worker safety constraints. In this system, the daily lettuce production was about 132 heads and potential annual production (360 harvests) was 47,520 heads.

The cultivation room of the adapted automated transporting system has a larger total growing area and higher planting density than the nonadapted automated transporting system. The total growing area on 35 m^2 of floor area is 129.6 m^2 in an adapted automated transporting system cultivation room and 59.4 m^2 in a normal nonadapted cultivation room. Planting densities are 108 heads/m^2 in an adapted automated transporting system and 75.4/m^2 in a normal cultivation room with a nonadapted system.

Each production cost was calculated during the trial using the following conditions. Running cost and production amount of the nonadapted system were both set at one third of those in the adapted system. Number of workers in both systems were set at 1.5. The results show production cost in the automated cultivation system is about 21% lower than the nonautomated system.

It is to be considered that production efficiency was increased through the use of an automated transporting system and that the workload for the same worker was also increased. It was also observed that the employment cost rate in the automated cultivation system was lower than the nonautomated cultivation system.

In addition to increasing the size of the plant factory, ongoing automation (such as cleaning, transporting, packing, and managing) productivity will be increased and workload decreased.

4.1.6 DISCUSSION

Unlike a sunlight type plant factory, an artificial light type plant factory can make efficient use of space because of multistage cultivation. Efficient use of space affects production amount and cost. Results show that increasing the number of levels increases production amount and decreases production cost. However, it is certain that there are limitations related to worker safety and the efficiency of work in high places.

In a plant factory with high-rise and multilevel shelves, worker safety, efficiency, and increased production will be secured by using an automated transporting system. This is especially important in an artificial light type plant factory, where an increase of production and a decrease of electricity charges and employment pay are important for reducing production costs. Automation of cultivation systems can decrease the workload for production amount and also increase the production amount without increasing the number of workers. Therefore, it can reduce employment costs.

Furthermore, automated cultivation systems in a plant factory can offer work opportunities for elderly and handicapped people who can't work for many hours as able-bodied people.

This provides an opportunity for job creation, social contribution, and economic support from the government [1]. Automation and increasing the size in plant production systems are underway for reducing production and running cost. Automation and increasing size can create opportunities for employment and social contribution.

As mentioned above, results suggest that automation in an artificial light type plant factory decreases running costs and increases productivity. In addition, it also creates new job opportunities and social contribution. However, because of the high initial cost, it is recommended that preparations are made for automation that consider production scale, product, and sale destinations before designing the plant factory.

4.1.7 CONCLUSIONS

Plant factories in Japan are becoming the stage of new competition as scaling up to 10,000 and 20,000 shares has progressed. These new plant factories are not yet fully automated or mechanized.

We will continue to work on the development of automation technology in plant factories as we expect the expansion of production scale will continue in the future.

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CHAPTER

4.2

Energy Consumption and Heat Sources in Plant Factories

Ryohei Yokoyama

Department of Mechanical Engineering, Osaka Prefecture University, Sakai, Japan

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4.2.1 INTRODUCTION

It is generally told that the cost for electricity consumption shares about 30% of the production cost in plant factories using artificial light. According to a test calculation of the production cost, the variable cost shares 36% of the production cost and the electricity cost shares 91% of the variable cost [1]. In this calculation, it is assumed that fluorescent light is used. Even if LED light is used in place of fluorescent light to reduce electricity consumption, it is no exaggeration to tell that the electricity cost shares a large part of the production cost.

A large amount of thermal energy for air conditioning is also consumed to keep the ambient temperature appropriately under artificial light. There are several types of equipment for heat sources to supply thermal energy. One is electricity-driven type such as motor-driven heat pump, and another is fuel-fired type such as gas engine-driven heat pump and gas-fired absorption refrigerator. In addition to these types which supply only thermal energy, there is cogeneration type which supplies electricity and thermal energy simultaneously. It is driven

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by gas engine, diesel engine, etc. Although exhaust gas generated by gas engine-driven cogeneration is usually disposed of into the environment in commercial buildings, carbon dioxide included in exhaust gas may be utilized to promote growing plants in plant factories. This type is called trigeneration.

In this section, energy supply by heat pump or cogeneration in plant factories using artificial light is investigated. The amounts of primary energy consumption and CO_2 emission in supplying energy by heat pump or cogeneration are evaluated based on electricity consumption estimated at the design phase of the plant factory using artificial light at Osaka Prefecture University [2]. In addition, it is investigated how carbon dioxide included in exhaust gas generated by cogeneration can be utilized to promote growing plants by trigeneration.

4.2.2 HEAT PUMP

In one type of energy supply for plant factories, electricity is purchased from an electric power company, and thermal energy is supplied by heat source equipment. Heat pumps are typical heat source equipment and are driven by electric motors using electricity or gas engines using city gas. Since the coefficient of performance (COP) of heat pumps, which is an important performance indicator, has been enhanced recently, multi-split type heat pumps have been used for air conditioning in commercial buildings. Both the motor-driven and gas engine-driven heat pumps have been used in commercial buildings. However, the former rather than the latter are used in plant factories, since it is easier to control the ambient temperature appropriately by the former.

The energy conversion of a heat pump is shown in Fig. 4.2.1. The heat pump converts heat with a low temperature to heat with a high temperature using power. In the case that heating energy is supplied for space heating, the purpose of the heat pump is to produce heat with a high temperature, and heat with a low temperature is obtained from the environment. On the other hand, in the case that cooling energy is supplied for space cooling, the purpose of the heat pump is to produce heat with a low temperature, and heat with a high temperature is obtained from the environment. The latter case corresponds to thermal energy supply in plant factories using artificial light. The COPs are defined as the ratios of heating and cooling energies to power consumption in the former and latter cases, respectively. If heat loss is neglected, the sum of cooling energy and power consumption equals heating energy because of the law of energy conservation. Since cooling energy is usually larger than power consumption, the COPs in both the cases are greater than 1.0. This means that power

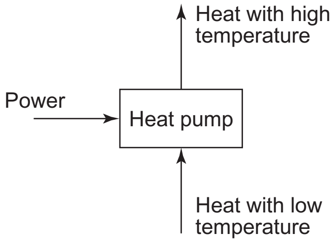

FIG. 4.2.1 Energy conversion of heat pump.

consumption is smaller than heating and cooling energies, although the quality of power is much higher than those of heating and cooling energies. It should be noted that the COP depends significantly on the temperatures of heating and cooling energies, or the temperatures of the outside environment and inside ambient air, respectively, in plant factories. Thus, the COP and power consumption change with season and time, even if cooling energy is constant.

4.2.3 COGENERATION AND TRIGENERATION

In another type of energy supply for plant factories, electricity and thermal energy are supplied simultaneously by cogeneration equipment. Gas engines, diesel engines, etc. are typical prime movers for cogeneration equipment. The energy conversion of cogeneration is shown in Fig. 4.2.2. with that of a heat engine, which is the general term for gas engines, diesel engines, etc. Power is produced by utilizing the difference between heats with high and low temperatures. Heat with a high temperature is obtained by combusting fuel. Power is generated by driving a generator by the heat engine using heat with a high temperature. Heat with a low temperature is obtained by exhaust heat generated from the heat engine. If the heat engine is used only for power generation, heat with a low temperature is disposed of to the environment. In this case, the thermal efficiency is defined as the ratio of power generation to heating value of combusted fuel. If heat loss is neglected, heat with a high temperature equals the sum of power generation and heat with a low temperature because of the law of energy conservation. If the heat engine is used for cogeneration, part of heat with a low temperature is recovered to utilize it for thermal energy supply such as space heating, space cooling, and hot water supply. In this case, the thermal efficiency is defined as the ratio of the sum of power generation and recovered heat with a low temperature to heating value of combusted fuel. Thus, the thermal efficiency of cogeneration is higher than that of only power generation. Since thermal energy recovered by cogeneration is heating one, it should be converted to cooling one by absorption refrigerators to utilize it in plant factories using artificial light.

Although power and thermal energy are supplied simultaneously by cogeneration, the ratio of thermal energy to power supplied by cogeneration (heat to power supply ratio) cannot be changed flexibly. Thus, if the ratio of thermal energy to power demanded by a user (heat to power demand ratio) coincides the heat to power supply ratio, the thermal efficiency is

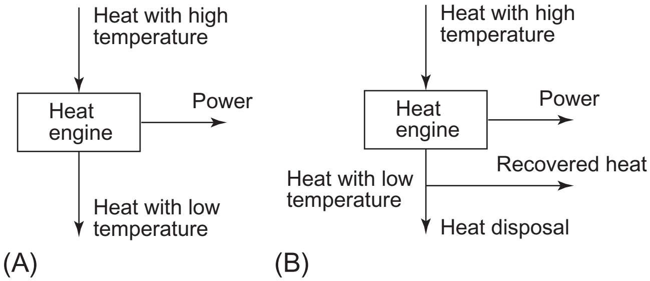
Heat with high temperature
Heat engine
Power
Heat with low temperature
(A)
Heat with high temperature
Heat engine
Power
Recovered heat
Heat with low temperature
Heat disposal
(B)

FIG. 4.2.2 Energy conversion of heat engine and cogeneration. (A) Heat engine; (B) cogeneration.

enhanced. For this purpose, it is necessary to install a cogeneration equipment with the maximum power and thermal energy supplies smaller than the minimum power and thermal energy demands, respectively. However, it is necessary to supplement the shortages of power and thermal energy by purchasing power and producing thermal energy with auxiliary boilers, respectively. Thus, it is also necessary to evaluate the thermal efficiency of the cogeneration equipment in combination with purchasing power and auxiliary boilers. On the other hand, if a cogeneration equipment with the maximum power and thermal energy supplies larger than the minimum power and thermal energy demands, respectively, is installed, this situation leads to a large increase in the investment cost as well as operation at part loads to avoid reversed power and disposal of part of recovered thermal energy. As a result, it leads to a decrease in the thermal efficiency. In plant factories using artificial light, it is expected that power and thermal energy demands are more stable than those in commercial buildings. However, since the power and thermal energy demands change with season and time, it is important to design and operate the cogeneration equipment appropriately in consideration of them.

In addition to power and thermal energy supplies by cogeneration, carbon dioxide included in exhaust gas generated from the heat engine may be utilized. The concentration of carbon dioxide in the field where plants are grown is increased to promote growing plants. This trigeneration has been tried in some fields. However, the amount of carbon dioxide may be small as compared with those of power and thermal energy supplies, and thus large part of carbon dioxide may be disposed of.

4.2.4 EVALUATION OF PRIMARY ENERGY CONSUMPTION

Economic feasibility may be the most important criterion to materialize plant factories. However, energy consumption and CO_2 emission may also be important criteria. In this subsection, the primary energy consumption is evaluated using a typical specification for plant factories using artificial light. The electricity consumption estimated at the design phase of the plant factory using artificial light at Osaka Prefecture University is used as basic data [2].

It is assumed here that 5000 heads of lettuce are produced every day throughout a year in a plant factory. The contents and total of the annual electricity consumption as well as the electricity consumption necessary for producing a head of lettuce are estimated as shown in Table 4.2.1.

TABLE 4.2.1 Electricity Consumption for Growing Lettuce

Item	Annual Energy Cons. (MWh/y)	Energy Cons. per Head (kWh)
LED light	1906	1.044
Air conditioning by heat pumps	1232	0.675
Production facilities	478	0.262
Total	3616	1.981

First, the primary energy consumption for producing lettuce is evaluated in the case that electricity is purchased from an electric power company and motor-driven heat pumps are used for air conditioning. If it is assumed that the energy conversion efficiency of purchased electricity is 0.369, its reciprocal or the coefficient for converting the electricity consumption to the primary energy consumption is 2.71 kWh/kWh. As a result, the primary energy consumption for producing a head of lettuce is 5.369 kWh. However, it should be investigated how large or small this value is in comparison with some reference values. Here, the domestic total primary energy consumption per person in Japan is used as a reference value. According to the statistical data in the Japanese fiscal year 2011 [3], the domestic total end-user energy consumption per person in Japan is 3.433 kWh/h, and it is converted to the domestic total primary energy consumption per person in Japan of 5.356 kWh/h. If it is assumed that the metabolic rate of a person, which is obtained by eating and drinking, is 0.112 kWh/h (96 kcal/h), the above domestic total primary energy consumption per person in Japan is 47 times as large as the metabolic rate. On the other hand, if it is assumed that the metabolic rate of a person is obtained only by eating lettuce, a head of which has a calorific value of 0.070 kWh (60 kcal), the person has to eat 1.6 heads of lettuce per hour, and the primary energy consumption for producing 1.6 heads of lettuce per hour amounts to 8.588 kWh/h as shown in Fig. 4.2.3., which is 76 times as large as metabolic rate of the person. Thus, the primary energy consumption for producing lettuce exceeds the domestic total primary energy consumption per person in Japan.

Second, the primary energy consumption for producing lettuce is evaluated in the case that cogeneration is used to supply electricity and thermal energy for air conditioning. If it is assumed that the power generating and exhaust heat recovery efficiencies of the cogeneration is 0.35 and 0.45, respectively, and that the electricity consumption of 2.089 kWh/h for LED light and production facilities is supplied by the cogeneration as shown in Fig. 4.2.4., the recovered exhaust heat is 2.686 kWh/h. If this heat is used as the heat source, and an absorption refrigerator with a COP of 0.7 is operated, cooling energy of 1.880 kWh/h is obtained. In this case, cooling energy of 1.360 kWh/h is in short supply. If this shortage is neglected, the primary energy consumption only for the cogeneration is 5.969 kWh/h, which is 53 times as large as the metabolic rate of the person. Thus, the primary energy consumption for producing lettuce is comparable with the domestic total primary energy consumption per person in Japan. If the cooling energy of 1.360 kWh/h is supplied additionally by motor-driven heat pumps with a COP of 3.0, the primary energy consumption only for the heat pumps is 1.229 kWh/h. Thus, the total primary energy consumption is 7.198 kWh/h, which is 64 times

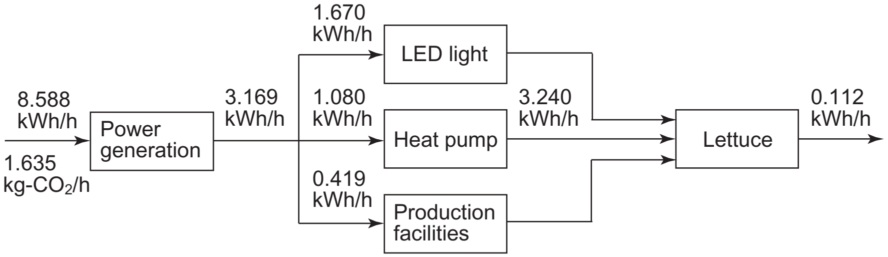

FIG. 4.2.3 Primary energy consumption and CO_2 emission by using heat pump for growing lettuce.

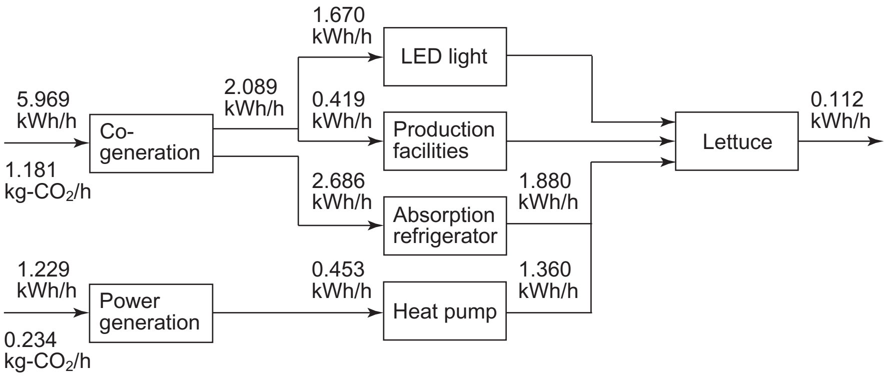

FIG. 4.2.4 Primary energy consumption and CO_2 emission by using cogeneration for growing lettuce.

as large as the metabolic rate of the person. Thus, the primary energy consumption for producing lettuce exceeds the domestic total primary energy consumption per person in Japan.

The aforementioned evaluation shows that it is no exaggeration to tell that much energy is consumed even if LED light is used in plant factories. The electricity consumption for producing a head of lettuce may be only 2 kWh, and the corresponding electricity cost may be only 40–50 yen. However, the corresponding primary energy consumption is comparable with or over the domestic total primary energy consumption per person in Japan.

The energy consumptions to grow some vegetables in open fields and greenhouses have been compared [4]. It has been shown that the energy consumptions to grow vegetables in greenhouses are 5–29 times as large as those in open fields, and are 26–132 times as large as the calorific values of the vegetables. In addition, the energy consumption of plant factories using artificial light has been evaluated, and the annual primary energy consumption per annual sale has been compared for a variety of industries [5]. It has been recognized how large the energy consumption of plant factories is as compared with the other industries.

4.2.5 EVALUATION OF CO_2 EMISSION

In this subsection, the CO_2 emission is evaluated using the same typical specification for plant factories using artificial light. The same electricity consumption estimated at the design phase of the plant factory using artificial light at Osaka Prefecture University is used as basic data [2].

First, the CO_2 emission by producing lettuce is evaluated in the case that electricity is purchased from an electric power company and motor-driven heat pumps are used for air conditioning. If it is assumed that the coefficient for converting the electricity consumption to the CO_2 emission is 0.516 kg-CO_2/kWh, the CO_2 emission for producing a head of lettuce is 1.022 kg-CO_2. It should also be investigated how large or small this value is in comparison with some reference values. Here, the domestic total CO_2 emission per person in Japan is used as a reference value. According to the aforementioned statistical data in the Japanese fiscal year 2011 [3], the domestic total CO_2 emission per person in Japan is 1.045 kg-CO_2/h.

If it is assumed that the CO_2 emission by breathing of a person is 0.036 kg-CO_2/h, the above domestic total CO_2 emission per person in Japan is 29 times as large as that by breathing of the person. On the other hand, if it is assumed that the metabolic rate of the person is obtained only by eating lettuce, the CO_2 emission by producing 1.6 heads of lettuce per person amounts to 1.635 kg-CO_2/h as shown in Fig. 4.2.3., which is 45 times as large as that by breathing of the person. Thus, the CO_2 emission by producing lettuce exceeds the domestic total CO_2 emission per person in Japan.

Second, the CO_2 emission by producing lettuce is evaluated in the case that cogeneration is used to supply electricity and thermal energy for air conditioning. If it is assumed that the cogeneration uses methane as a fuel, and that its heating value and CO_2 emission are 13.9 kWh/kg and 2.75 kg/kg, respectively, the CO_2 emission only by the cogeneration is 1.181 kg-CO_2/h as shown in Fig. 4.2.4., which is 32 times as large as that by breathing of the person. Thus, the CO_2 emission by producing lettuce is comparable with the domestic total CO_2 emission per person in Japan. If the cooling energy of 1.360 kWh/h is supplied additionally by motor-driven heat pumps with a COP of 3.0, the CO_2 emission only by the heat pumps is 0.234 kg-CO_2/h. Thus, the total CO_2 emission is 1.415 kg-CO_2/h, which is 39 times as large as that by breathing of the person. Thus, the CO_2 emission by producing lettuce exceeds the domestic total CO_2 emission per person in Japan.

4.2.6 EVALUATION OF CO_2 UTILIZATION

Finally, it is investigated how carbon dioxide included in exhaust gas can be utilized to promote growing plants by trigeneration in the case that cogeneration is used to supply electricity and thermal energy for air conditioning. The same electricity consumption estimated at the design phase of the plant factory using artificial light at Osaka Prefecture University is used as basic data [2].

If the same conditions are given to the cogeneration, the CO_2 emission by producing 1.6 heads of lettuce per hour is 1.181 kg-CO_2/h as described previously. On the other hand, it is estimated that carbon dioxide of 80 kg/d is consumed so that the CO_2 concentration of 1000 ppm is kept to promote growing lettuce in the plant factory at Osaka Prefecture University. This value means that carbon dioxide of 0.026 kg-CO_2/h is consumed to produce 1.6 heads of lettuce per hour. Thus, even if trigeneration is used, the amount of carbon dioxide which can be utilized to promote growing plants is only 2% of the CO_2 emission, and the remaining carbon dioxide has to be disposed of into the environment. If the capacity of the cogeneration is decreased and electricity is supplied by the cogeneration and purchased electricity, the ratio of carbon dioxide which can be utilized to promote growing plants can be increased. However, the amount of carbon dioxide which can be utilized to promote growing plants cannot be increased, while the effect of electricity and thermal energy supplies by the cogeneration is decreased.

4.2.7 CONCLUSIONS

The aforementioned results show not only that plant factories using artificial light should satisfy economic feasibility, but also that use of energy sources and impact on global environment should be taken into account by evaluating the primary energy consumption and CO_2 emission. There may be several objectives of plant factories. If bad harvest due to abnormal weathers by global warming is supplemented by plant factories, it is necessary to investigate validity of using plant factories carefully. The operation of plant factories using artificial light may increase CO_2 emission and accelerate global warming.

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CHAPTER

4.3

Advanced Technologies for Pollination in Plant Factories

Hiroshi Shimizu
Graduate School of Agriculture, Kyoto University, Kyoto, Japan

OUTLINE

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4.3.1 INTRODUCTION

It is common to use bees for pollination of strawberries and tomatoes. Originally, bees are insects that move with ultraviolet rays, but in an environment inside a plant factory with artificial light, only the light source including only a part of the wavelength region necessary for plant growth is often used, and the wavelength of ultraviolet region necessary for bees is not included. It has been reported that honeybees, a pollinating insect, are hampered in feeding activity in green houses coated with ultraviolet ray removal film and do not produce effective pollination [1]. Also, scattered honey bee dead bodies and hunts inside the plant may adversely affect sanitary environments inside plant factories. Plant factories with artificial light generally have low risk of dust, bacteria, and pest infestation. However, an environment suitable for plants is often suitable for bacteria and pests, and even a slight invasion may cause serious damage. It is easy to predict risk when the honeybees are released at a plant factory that requires such a high clean environment.

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Furthermore, there are reports that bees are decreasing worldwide, and it is becoming difficult to obtain honey bees. This is called Colony Collapse Disorder (CCD) and is a problem in many parts of the world. According to a survey conducted in 2007, one quarter of the nation's beekeepers experienced a mass disappearance of bees and it turned out that more than 30% of nest boxes were annihilated [2]. Also, from 2007 to 2008, 36% of beekeepers throughout the country have been damaged and have been reported from Australia, Brazil, Canada, China, Europe, and others. However, the main cause of the CCD has not been determined yet. Several papers pointed out the involvement of insecticide neonicotinoid, but other factors such as fungicides, drought, and biased bait are also considered to be related [3]. Also in Japan, honey bees for pollination are short due to mass death, etc., and the Ministry of Agriculture, Forestry and Fisheries announced the survey result that the bees are short in 21 prefectures nationwide in April 2009 [4]. The Ministry of Agriculture, Forestry and Fisheries has reported that the problem of shortage of bees has not occurred since 2010 due to adjustment of supply and demand, but acknowledges that the bee production and distribution base still has a vulnerable aspect. Then, Shimizu et al. [5] developed a noncontact pollination system using ultrasonic waves as an alternative to bee pollination.

4.3.2 SYSTEM DESCRIPTION

4.3.2.1 Ultrasonic Focusing Device

In this study, an ultrasonic focusing device was used as a device to vibrate flowers and pollinate by ultrasonic waves. The specifications of the ultrasonic focusing device are shown below [6] (Table 4.3.1).

This ultrasonic focusing device was developed by Hoshi et al. [6] as a tactile display that generates working force without contact. Two hundred and eighty five ultrasonic transducers are mounted on the front surface of the ultrasonic focusing device, and ultrasonic waves are

TABLE 4.3.1 Specifications of Ultrasonic Focusing Device

Target Area	$20 \times 20 \times 40\,\text{cm}^3$ (reference)
Position resolution	0.5 mm
Focal diameter	20 mm (focal length is 20 cm)
Occurrence	Maximum 16 mN (624 steps)
Communication	USB
Time delay	1 ms (transducer rise time)
Power supply	24 V
Power consumption	100 W (ultrasonic output)
Size	$19 \times 19 \times 5\,\text{cm}^3$
Weight	0.6 kg
Number of transducers	285 pieces

generated from each transducer. Although the radiation pressure of ultrasonic waves generated from each transducer is very small, ultrasonic waves can be focused to one point by phased array technology and large radiation pressure can be generated (Fig. 4.3.1). Since the position of the focal point can also be changed by controlling the phase, a force can be generated at any position in the three-dimensional space. Using this technique, ultrasonic waves are irradiated to the position of the flower measured by the 3D camera, and the flower is vibrated.

Also, ultrasonic wave of frequency 40 kHz was irradiated from the ultrasonic focusing device, but it was pseudo-modulated to low frequency by pulse irradiation (Fig. 4.3.2). This makes it possible to generate acoustic waves of a frequency at which strawberry flowers can be vibrated while maintaining high directivity of ultrasonic waves.

4.3.2.2 RealSense 3D Camera

3D cameras RealSense 3D Camera (Intel, hereinafter referred to as RealSense) capable of acquiring distance information was used in order to obtain position information of strawberry flowers in three-dimensional space. The specifications are shown in Table 4.3.2. Fig. 4.3.3 shows an ultrasonic pollination apparatus constructed by combining "Ultrasonic focusing device" and "RealSense 3D Camera."

4.3.2.3 Image Acquisition

Color images and distance images are acquired from 3D cameras. A color image is acquired with a size of 640 × 480, and each pixel contains RGB information. Distance information was

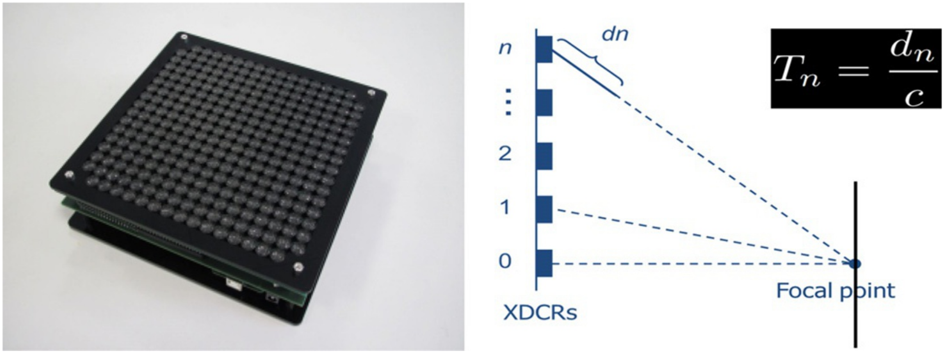


FIG. 4.3.1 Ultrasonic focusing device (left) and phased array (right).

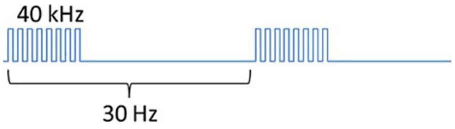


FIG. 4.3.2 Modulation method.

TABLE 4.3.2 RealSense Specifications

	RealSense 3D Camera
Color image resolution	1920 × 1080
Color image frame rate	30FPS
Distance data resolution	640 × 480
Distance data frame rate	60FPS
Distance recognition range	200–1200 mm

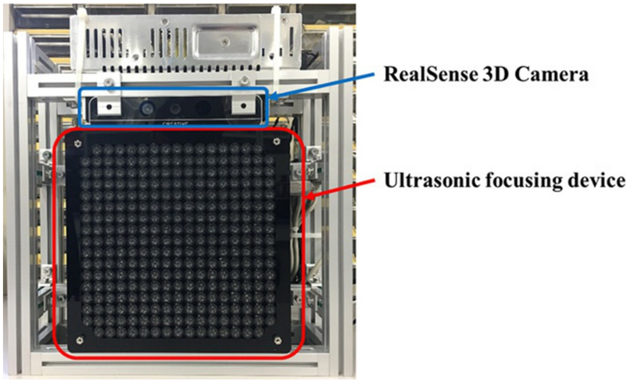


FIG. 4.3.3 Appearance of developed device.

acquired in the range of 200–1200 mm, and other ranges were excluded from recognition. Data of 200–1200 mm was equally divided into 256 parts and applied to grayscale data to convert the distance data so that it can be an output as an image.

4.3.2.4 Contour Extraction

Next, contour extraction of the image was carried out to clarify the area of flowers of strawberry. In this process, the obtained color image was first converted to grayscale, and contour was extracted by using the Canny function for this gray image. Since contour extraction is sensitive to noise in the image, first the image was smoothed and noise was reduced. Next, the luminance gradient and direction of the image were obtained from the following formula.

$$\text{Gradient of luminance}\,(G) = \sqrt{G_x^2 + G_y^2}$$

$$\text{Direction}\,(\theta) = \tan^{-1}\left(\frac{G_y}{G^x}\right)$$

In the above equation, G_x and G_y are values obtained by first differentiating the image in the vertical direction and the horizontal direction, respectively. An adjacent pixel having a large luminance gradient is a portion in which a large color change has occurred and is highly likely to be a contour. After calculation of the gradient direction and intensity, pixels that are not related to the contour are removed.

The contour image created by this processing is further expanded/degenerated to remove noise. In this process, it is possible to clearly distinguish the contour from the others by repeating the dilation process in which the pixel in contact with the contour pixel is similarly regarded as a contour and the degeneracy process in which the pixel in contact with the pixel other than the contour is regarded as being other than the contour in the same manner. In this system, the outline which is thicker than the outline obtained by the Canny function was obtained by performing expansion 4 times and degeneracy 3 times.

4.3.2.5 Color Averaging

Using the contour image obtained in the previous section, a process of averaging the color of the area surrounded by the outline is applied. By averaging the colors in the contour, the color of each object can be clarified, and identification by color is easy.

In addition, even in the region containing halated leaves, it is considered that the difference in color from strawberry flower appears clearly by taking the average with the nonhalation part. As a processing method, firstly, the contour image created in the previous section is superimposed on the color image, labeling is performed, and the RGB information in the labeled region is summed and divided by the number of pixels to calculate the average value of the RGB information in the region. An image obtained by averaging colors for each label is as shown in Fig. 4.3.4.

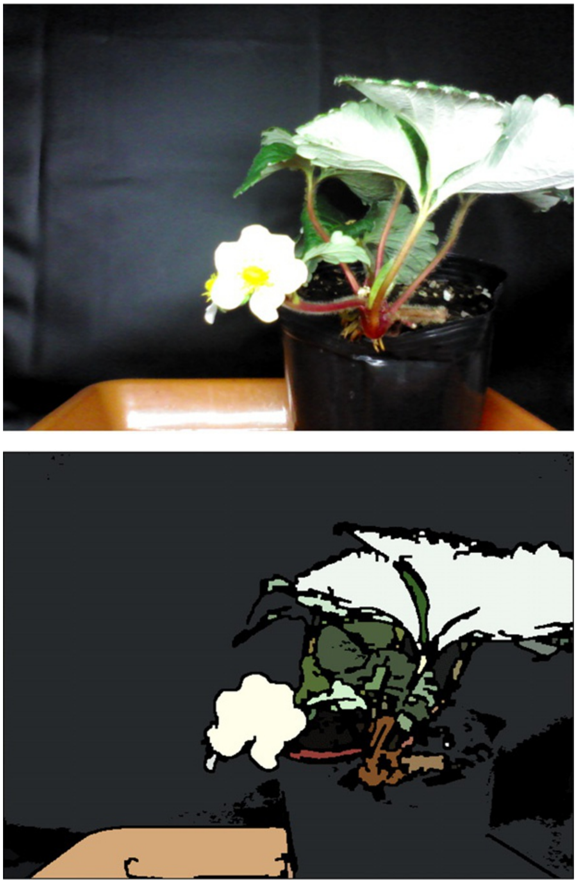
4.3.2.6 Strawberry Flower Recognition by Learning Model

Strawberry flowers were recognized by a learning model by Support Vector Machine using the averaged images. The RGB information in each area on the averaged image is input to the strawberry flower recognition model, and it is judged whether or not the color of the area is the same color as the strawberry flower, thereby determining the strawberry flower candidate on the image. Among the areas considered to be candidates for strawberry flowers in this processing, the area apparently not as a flower was removed as noise. First, a threshold relating to the size of the region is provided, the size of the region considered as a flower is set to 200 pixels or more and 10,000 pixels or less, and the other regions are removed as noise. Next, a threshold based on the distance is provided. An area with a certain distance from the camera was excluded from the strawberry flower candidates as the background. On the farm where strawberry flowers were taken, the distance between the camera and strawberry was roughly 20–40 cm, so the area to be removed was set more than 40 cm away from the camera.

4.3.3 POLLINATION EXPERIMENT

Pollination experiment was conducted in a greenhouse (Fig. 4.3.5). We aimed not only to investigate the effect of ultrasonic pollination, but also to investigate an appropriate modulation frequency of ultrasonic waves. By setting an appropriate modulation frequency, it is

FIG. 4.3.4 Image before averaging (top) and averaged image (bottom).



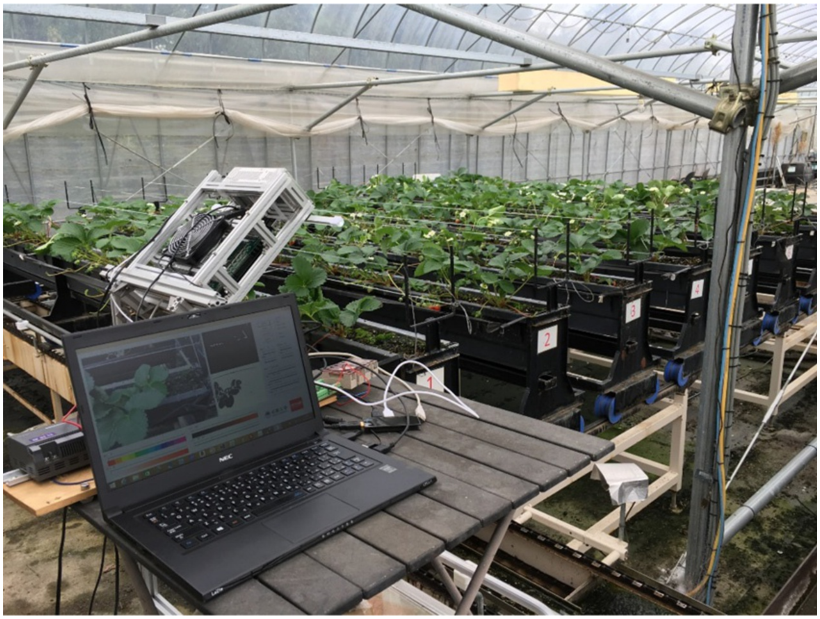


FIG. 4.3.5 Pollination experiment in greenhouse.

possible to carry out the pollination process more efficiently, and improvement of the fruit yield rate is expected.

In this experiment, ultrasonic pollination section (10 experimental groups) and brush pollination section (2 experimental groups) and untreated section (2 experimental groups) were provided to study the effect of ultrasonic pollination. Furthermore, in order to investigate an appropriate modulation frequency, experiments were conducted by dividing the modulation frequency of the ultrasonic pollination zone into 10 divisions at intervals of 10 Hz from 10 to 100 Hz (Table 4.3.3). The number of irradiation of ultrasonic waves was once per flower and the irradiation time was 2 s.

4.3.4 RESULTS AND DISCUSSION

The number of salable fruit and salable fruit rate in each experimental section are shown in Table 4.3.3. In the ultrasonic pollination section, the salable fruit ratio was 91.7% at the maximum, but it was 36.4% in some cases. Regarding the brush pollination section, the salable fruit ratio was about 60% in both sections. Although there were variations in the untreated section, both were low values.

Regarding the result for each frequency in the ultrasound pollination zone, in this ultrasonic pollination zone, the allowable fraction ratio was 91.7% when the modulation frequency was 40 Hz, showing the best result. If changes in the fruit yield and malformed fruit

TABLE 4.3.3 Experimental Result of Ultrasonic Pollination

Modulation Frequency		Number of Flowers	Number of Salable fruit	Salable fruit Ratio (%)
Ultrasonic pollination	10 Hz	16	9	56.3
	20 Hz	20	12	60.0
	30 Hz	9	7	77.8
	40 Hz	12	11	91.7
	50 Hz	18	8	44.4
	60 Hz	11	4	36.4
	70 Hz	17	12	70.6
	80 Hz	14	7	50.0
	90 Hz	17	7	41.2
	100 Hz	16	10	62.5
Brush pollination (1)		12	7	58.3
Brush pollination (2)		7	4	57.1
No treatment (1)		19	8	42.1
No treatment (2)		10	2	20.0

occurrence rate appear depending on the frequency, it is believed that the cause is due to the physical behavior of strawberry flowers during ultrasonic irradiation. Amplitude is one of the indices of this behavior. Therefore, the amplitude of each frequency was investigated using a high-speed camera. A strawberry flower was shot under vibration with a high-speed camera and its amplitude was measured. As a result, the maximum amplitude was obtained at 10 Hz, but no significant difference was observed at 30–100 Hz (ANOVA 4 analysis of variance, significance level $P = .05$). Since there is no correlation between this result and the results of the pollination test, it is considered that the amplitude has little effect on pollination of strawberries. Therefore, it was suggested that further pollination situation evaluation method should be developed to clarify the characteristics of each frequency.

Next, comparison of ultrasonic pollination at 40 Hz, which was the best result, brush pollination, and no treatment, revealed that the ultrasonic pollination zone at 40 Hz shows the highest salable fruit ratio. In ultrasonic pollination, it is possible to exactly excite only the flowers of strawberry and evenly pollinate the pistil by using ultrasonic waves of high directivity. Therefore, it is thought that the occurrence of malformations was suppressed and the salable fruit ratio increased. On the other hand, in the brush pollinated section, the salable fruit ratio was higher than that in the untreated plot. Because it was done by hand, there was a part where pollen was not adhered, causing a decrease in the salable fruit rate.

The salable fruit ratio of ultrasonic pollination obtained is comparable to bee pollination in the same environment (data not shown) and it was shown that ultrasonic pollination apparatus could be an alternative to bees in pollination treatment. This ultrasonic pollination is currently being studied, but we are continuing our research aiming at commercialization in the near future.

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CHAPTER

5.1

A Study on Supercooled Storage of Leaf Lettuces Produced in Plant Factory

Nguyen Quang Thinh, Koji Iwamura, Nobuhiro Sugimura
Osaka Prefecture University, Graduate School of Humanities and Sustainable System Science, Dept. of Sustainable System Science, Sakai, Japan

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5.1.1 INTRODUCTION

Much emphasis is now being given to research and development of plant factories with fully closed and artificially controlled environment, aimed at producing various vegetables safely and constantly. Plant factories daily produce large amount of high quality vegetables under artificially controlled environments. However, the demands from the customers are not constant, and the unsold vegetables should be disposed due to their short shelf-life and the risk of foodborne illness after the short period of storages.

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The fresh vegetables are perishable and so require refrigeration in order to extend the shelf-life and to reduce the risk of foodborne illnesses. It is estimated that as much as 25%–30% of perishable food production is wasted and most of the wastage could be saved during postharvest storage by the correct use of refrigeration [1]. The plant factory of Osaka Prefecture University (OPU), for an example, constantly producing about 6000 bags of leaf lettuces every day is also equipped with a postharvest storage; however, the current storage has a limited capability for keeping the shelf-life of the produced leaf lettuces before shipping to markets or customers. Therefore, the large plant factories require more effective storage systems to improve the shelf-life duration.

Supercooled process is the process to keep the temperature of the fresh food below their usual freezing temperature without the phase changes from water to ice [2]. The supercooled is also called by several terms such as supercooling, undercooling [3–6], subcooled [7], and Hyo-On in Japanese [8]. The supercooled storage has been applied, aimed at improving the shelf-life duration for a variety of food including vegetables [5,9], fishes [8,10,11], and meats [12–14]. The application of supercooled storages on the tomatoes is also reported in a patent application [15].

In the other researches, the supercooled techniques are applied to various types of vegetables to examine the differences in the visual appearance under the fresh, frozen, and supercooled storage temperatures [16]. The effects in the variable temperature conditions have been studied to clarify the feasibility and crop production of the seed potatoes prior to planting [17].

The previous research works show that the supercooled technique is effective to improve the shelf-life duration for a variety of food including vegetables. Therefore, the supercooled techniques are applied to the vegetables produced in the plant factories, in the present research, to investigate its effectiveness for the mass produced and standardized leaf lettuces.

The objectives of this study are summarized in the following.

(1) To clarify the freezing temperature and the nucleation temperature of the leaf lettuces produced by the plant factories,
(2) To investigate the supercooled storage conditions and the effects of the supercooled storage for leaf lettuces, and
(3) To compare the supercooled preservation method and the conventional preservation method for the long-term storages.

5.1.2 PLANT FACTORIES AND THEIR NEEDS TO SHELF-LIFE DURATION

Osaka Prefecture University has established a research and development center for the plant factories and a pilot plant for lettuces since 2010, in order to carry out the joint research projects among the universities and the companies. Fig. 5.1.1 shows the outlines of the newest pilot plant equipped in 2014 and its production processes for producing about 6000 pieces of the frill lettuces and the batavia lettuces every day [18].

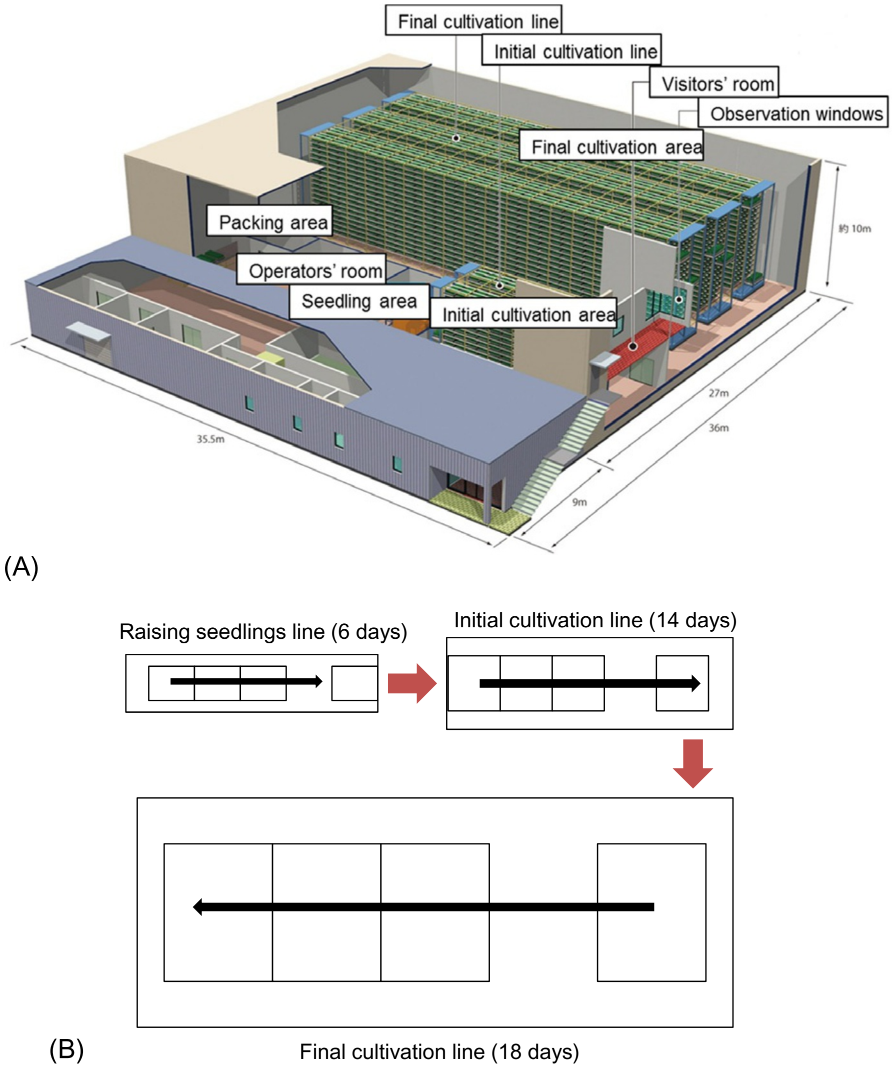

FIG. 5.1.1 Plant factory. (A) Bird's-eye view of a plant factory [3]. (B) Production processes in a plant factory.

As shown in Fig. 5.1.1A, the factory consists of a seedlings area, an initial cultivation area, a final cultivation area, a packing area, and an operators' room. The following four steps are required to produce the lettuces.

(1) Seedlings: The lettuce seeds are cultivated to the seedlings on the beds.
(2) Initial cultivation: The seedlings are transplanted onto the palettes and grown up to the sizes to be transplanted to the final cultivation area, since the sizes and the numbers of the palettes for two cultivation areas are different for saving the spaces in the plant factories.

(3) Final cultivation: The cultivated lettuces are transplanted onto the palettes in the final cultivation area. The area is composed of a set of transfer lines to transfer the palettes for one step forward every day to the outlet.

(4) Harvesting and packing: The grown-up lettuces are harvested and packed into the packages after the final cultivation process. The packed lettuces are stored in the refrigerators for one day to reduce their vital activity and to keep the shelf-life.

The production processes of the lettuces are thought to be a transfer line type production system shown in Fig. 5.1.1B, which includes three continuous lines. The processing time for the seedlings, initial cultivation, and final cultivation are 6 days, 14 days, and 18 days, respectively. In the production lines, the seeds are inputted to the seedling line and the lettuces are outputted from the final cultivation line every day.

The produced lettuces are delivered directly to the customers every day just after one day refrigeration, based on the daily customer orders. The customer orders are not constant, and so the unsold lettuces are stored in the refrigerators for few days. However, the shelf-life of the lettuces is limited, and unsold lettuces are finally disposed. Therefore, more effective preservation method is required for keeping the shelf-life in high quality for the long-term storage. The following sections deal with the application of the supercooled techniques to the fresh lettuces produced in the plant factories.

5.1.3 EXPERIMENTAL METHODS AND SAMPLES

5.1.3.1 Equipment and Samples

Fig. 5.1.2 shows the equipment for the supercooling experiments, consisting of an incubator refrigerator (CDB-14A, Taiwa Industrial, Corp., Japan), a set of thermo-sensors, a data-logger, and a computer. The experiments are designed for the leaf lettuces produced by the plant factory in Osaka Prefecture University, and the time series data of the temperatures in both the inside of the incubator refrigerator and the insides of the leaf lettuces are measured

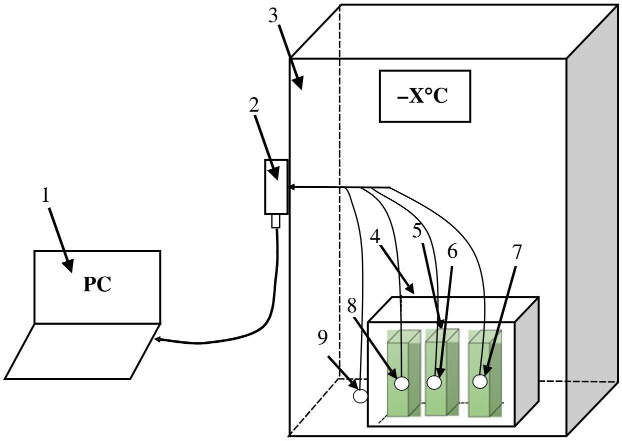

FIG. 5.1.2 Experimental equipment. 1: Computer; 2: Data-logger; 3: Incubator refrigerator; 4: Cardboard; 5: Samples; 6: Sensor 1; 7: Sensor 2; 8: Sensor 3; 9: Sensor 4.

and recorded by using the thermos sensors, data-logger, and the computer during the experiments.

The samples of the leaf lettuces are directly delivered from the plant factory every day for the experiments, so they are very fresh. The weights, sugar contents, and water contents of the individual samples are measured before the experiments and summarized in Table 5.1.1. The sugar content is measured by Pocket Refractometer PAL-J, Atago, Japan. The water content is measured by heating and drying-type moisture meter ML-50, A&D, Japan. The number of the bacteria in the samples is counted by applying 3M Petrifilm Aerobic Plate Count (APC) which is also known as Aerobic Colony Count (ACC), Standard Plate Count (SPC), Mesophilic Count, or Total Plate Count (TPC) in AOAC Official Method [19].

Three types of packages are considered and applied to the experiments as shown in Fig. 5.1.3, in order to investigate the effects of the packages. They are,

(1) Non-packed lettuces,
(2) Single packed lettuces, which are packed by the polypropylene (PP) bags with a suitable amount of oxygen inside the PP bags, and
(3) Double-layer packed lettuces in which the single packed lettuces are packed by a large PP bags to isolate the samples from the cold air flow in the refrigerator.

5.1.3.2 Experimental Conditions

5.1.3.2.1 Freezing Experiment

A series of trials are initially conducted to estimate both the nucleation temperature and the freezing temperature based on the freezing curves representing the temperature changes

TABLE 5.1.1 Initial Characteristics of Samples

	Weight (g)	Sugar Content (Brix %)	Water Content (%)
Mean	101.5	3.4	92
Min	78.5	3.2	90
Max	124.4	3.5	94

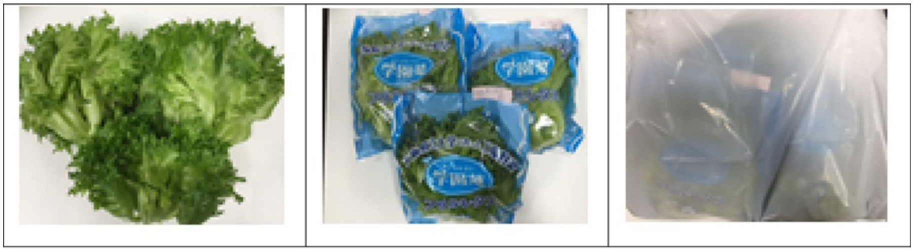
(a) Non-packed (b) Single packed (c) Double-layer packed

FIG. 5.1.3 Three types of packages. (A) Nonpacked, (B) Single packed, (C) Double-layer packed.

inside the lettuces. The temperature of the refrigerator is set in –10°C, in order to investigate the freezing temperature and nucleation temperature based on the freezing curves. So, the temperature in the inside of the refrigerator will be gradually changed from the room temperature to –10°C. Three single packed lettuces are set in the refrigerator and the thermo-sensors are set in the inside of the lettuces to measure the temperatures. When the temperatures of all samples reach to –7°C, it is assumed that the samples are frozen completely, and the experiments are terminated.

The nucleation temperature and the freezing temperature are estimated based on the freezing curves. The nucleation temperature is defined as the temperature at which some of the cells of the lettuces start to be frozen [5]. The nucleation temperature is experimentally obtained as a point at which the temperatures of the inside of the lettuces are rapidly increased due to the phase change from the water to the ice. The freezing temperature is the temperature represented as a plateau in the freezing curves where the measured temperature is almost constant [5]. The freezing temperature is obtained directly from the logged temperature data by selecting the temperature at which the change rate of the temperature is the minimum.

5.1.3.2.2 Investigation of Effects of Packages

The supercooled state is unstable and spontaneous nucleation may occur at any moment. Therefore, there is the risk that slight shock will cause the supercooled state to dissolve and ice crystal to form [11]. The temperature control and the product packages play an important role to maintain supercooled state. A series of experiments are conducted by applying three types of packages to investigate the effects of the package type on the supercooled state. All three types of lettuce samples are put in the refrigerator and the temperature is set from –1°C to –6°C. In the experiment, the temperature changes in the lettuces are measured to investigate the cooling rates in the various package conditions. It is also visually investigated whether the lettuces are frozen or not after the experiments for 2 days to investigate the phase changes.

5.1.3.2.3 Long-Term Storage Experiments

The long-term storages in both the supercooled state and the normal refrigeration state are investigated by the long-term storage experiments for 3 weeks. The temperature is set at 5°C in normal refrigeration experiments and at –3°C in supercooled experiments, respectively. In the long-term storage experiment, the weights and the sugar contents of all the samples are measured at the initial state just before the preservation experiments, and at the intermediate and final states in the three weeks' experiment. The Aerobic Plate Count (APC) of all the samples is also counted at the initial, intermediate, and final states in the experiment, in order to investigate the increase of the number of the bacteria during storage [19].

5.1.4 RESULTS AND DISCUSSION

5.1.4.1 Freezing Experiment

The freezing curves of the leaf lettuce samples obtained in the experiments are shown in Fig. 5.1.4. The package type and the preset temperature are the single packed samples

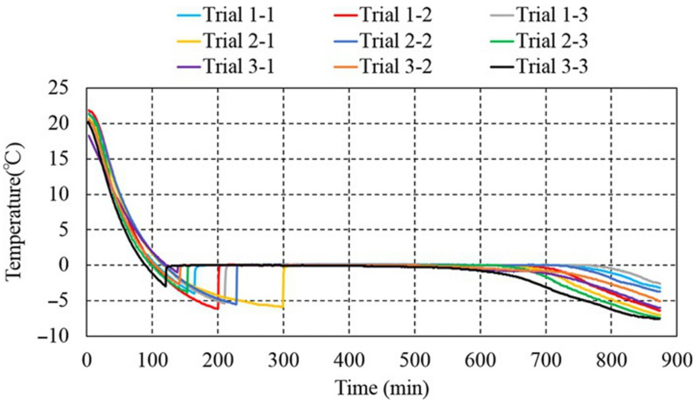

FIG. 5.1.4 Freezing curves of leaf lettuce samples.

and –10°C, respectively. The freezing experiments are carried out separately for three trials due to the limited capacity of the refrigerator, and the individual trials include three samples.

The nucleation temperature and the freezing temperature are obtained from the freezing curves and summarized in Table 5.1.2 for the individual samples. The nucleation temperature of the individual samples is different as shown in Fig. 5.1.4 due to the differences in the cooling rate measured inside of the samples. However, all samples are in the supercooled state between the temperature of –1°C and –6°C. The results give a possibility for supercooled storage, if the cooling conditions are suitably controlled. The minimum and maximum of the

TABLE 5.1.2 Nucleation Points and Freezing Points

Trials—Samples	Nucleation Temperature (°C)	Initial Freezing Temperature (°C)
1-1	–4.0	–0.3
1-2	–6.1	–0.2
1-3	–5.4	–0.2
2-1	–5.9	–0.1
2-2	–5.5	–0.1
2-3	–3.9	–0.2
3-1	–1.0	–0.1
3-2	–2.7	–0.1
3-3	–3.0	–0.3
Mean	–4.2	–0.2
Standard deviation	1.7	0.1
Min	–6.1	–0.3
Max	–1.0	–0.1

nucleation temperature is –6.1°C and –1.0°C, respectively. The freezing temperature of all the samples is almost same and estimated at –0.2°C.

5.1.4.2 Investigation of Effects of Packages

The temperatures in the inside of the leaf lettuce samples are obtained in the experiments as shown in Fig. 5.1.5A–C of the non-packed, single packed, and double-layer packed samples, respectively. All the non-packed samples reach to the frozen temperature and they are frozen. Three single packed samples keep the supercooled state without nucleation of the ice crystal and three ones are frozen within 8 hours. As regard the double-layer packed samples, all the samples keep the supercooled state during the first day. After that, only two samples are frozen in the second day. Therefore, the double-layer package is effective to keep the supercooled state during longer period.

Table 5.1.3 summarizes the cooling rate and the state of all the samples after two days. The table shows that the supercooled state is expanded, if the number of package layers is increased. The measured temperatures in the inside of the samples are almost same as the

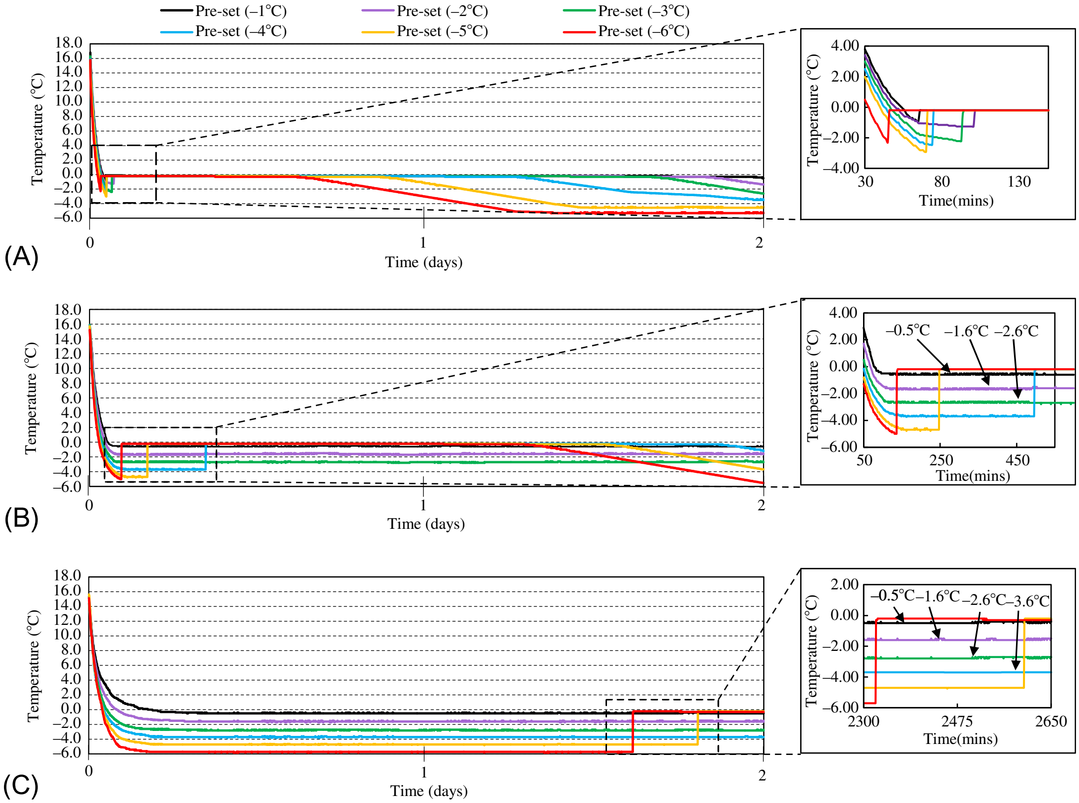

FIG. 5.1.5 Temperatures inside of samples packed by different packages. (A) Nonpacked, (B) Single packed, (C) Double-layer packed.

TABLE 5.1.3 Effectiveness of Packages

Preset Temperature (°C)	Non-Packed Cooling Rate/Frozen (°C min^{-1}/Yes-No)	Single Packed Cooling Rate/Frozen (°C min^{-1}/Yes-No)	Double-Layer Packed Cooling Rate/Frozen (°C min^{-1}/Yes-No)
–1	0.43/Yes	0.16/No	0.03/No
–2	0.65/Yes	0.17/No	0.04/No
–3	0.83/Yes	0.18/No	0.05/No
–4	0.90/Yes	0.19/Yes	0.06/No
–5	0.95/Yes	0.21/Yes	0.07/Yes
–6	1.00/Yes	0.22/Yes	0.08/Yes

Note: Yes: Frozen; No: Nonfrozen.

preset temperature and lower than the freezing temperature. For examples, in the case where preset temperature is –1°C, –2°C, and –3°C, the temperatures in the inside of the samples reach to –0.5°C, –1.6°C, and –2.6°C, respectively. This means that the lettuces are kept in the nonfrozen state under the supercooled conditions. The cooling rate is also important for the supercooled storages. As shown in the Table 5.1.3, the lettuces are frozen in the conditions of the higher cooling rate. Thus, the packages play an important role to keep the low cooling rate and to reduce the risk of being frozen in the supercooled state.

5.1.4.3 Long-Term Storage Experiments

In the long-term storage experiments, the temperature in the inside of three representative samples under supercooled conditions are measured and shown in the Fig. 5.1.6. The temperature in the inside of the sample reaches near to the preset temperature and is stable throughout for 1, 2, and 3 weeks of the storage time. This means that the samples are remained in the nonfrozen state under supercooled conditions.

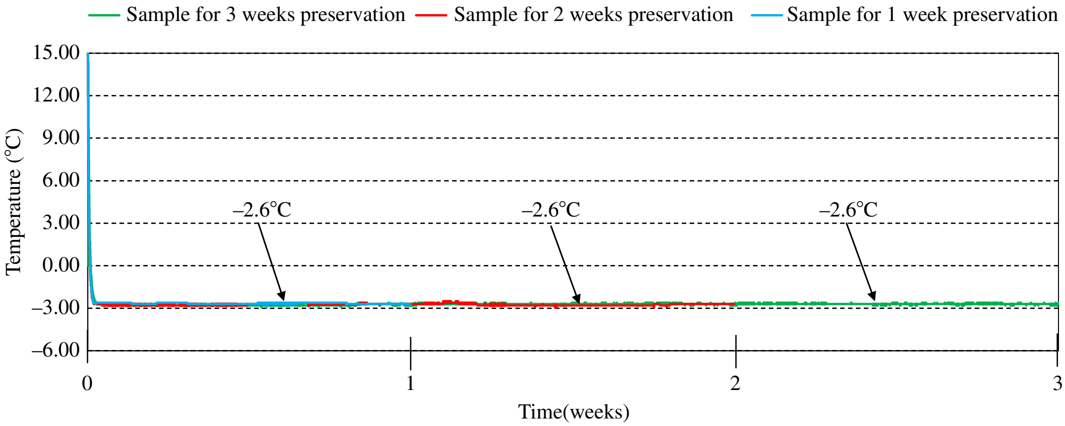

FIG. 5.1.6 Temperatures inside of samples in long-term storage.

The weight loss and the sugar contents are summarized in the Figs. 5.1.7 and 5.1.8, respectively. In the figures, 0 in the horizontal axis mean the date on which the storage experiments are started. The weight loss of samples stored under supercooled conditions is smaller than 3%. On the other hand, the weight loss of samples stored under normal refrigeration conditions is higher and reaches more than 8% at the end of the third week. The weight loss depends on many factors such as, the temperature, the humidity, and the oxygen in the circumstance surrounding the samples. The initial state of all the samples is almost same, since the samples are harvested at the same time and packed just after the harvesting. Therefore, the oxygen contents in the packages are thought to be almost same. As regards the temperature and the humidity, we have monitored only the temperature in both the normal refrigerator and the supercooling refrigerator due to the lack of the sensing systems.

The free sugar content of the samples is almost same in both cases of the normal refrigeration and the supercooled conditions. The mean values in the supercooled conditions are slightly higher after the 3-week storages; however, the statistical analysis will be required in the future for the detailed discussion.

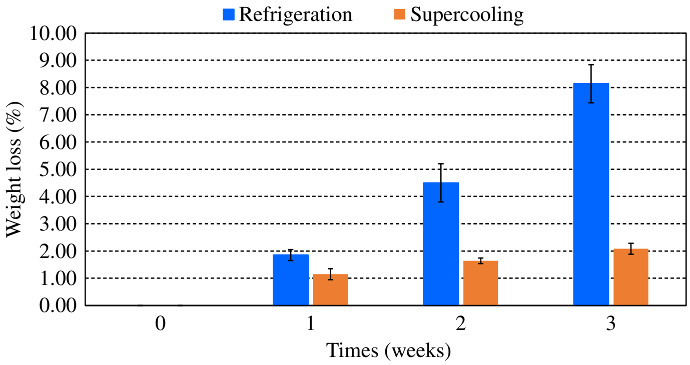

FIG. 5.1.7 Weight loss. Bar: Mean values, Line: Standard deviation.

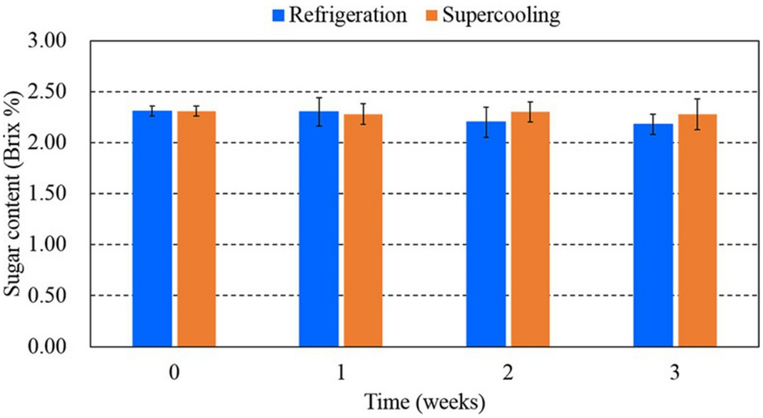

FIG. 5.1.8 Sugar content. Bar: Mean values, Line: Standard deviation.

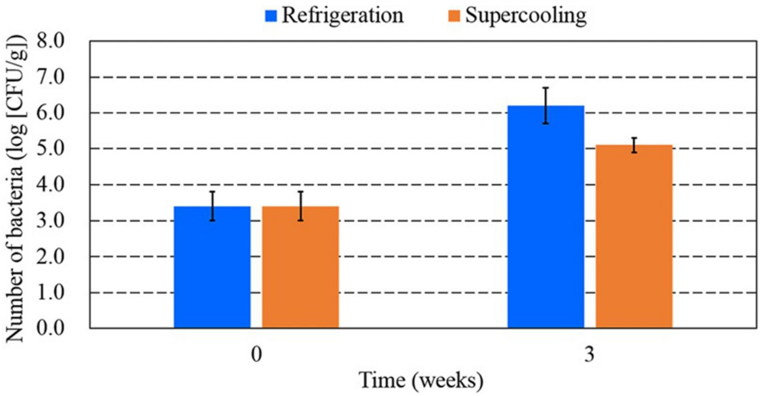

FIG. 5.1.9 Number of bacteria in every 1 g of samples. Bar: Mean values, Line: Standard deviation.

The numbers of the bacteria in the samples at the initial state and ones after the 3-week storages are shown in Fig. 5.1.9 for both cases of the supercooled conditions and the refrigeration conditions. As shown in the figures, the initial numbers of the bacteria are about $10^{3.4}$ [CFU/g] in both cases of the supercooled and refrigeration conditions. However, the numbers are increased, during the 3-week storages, to $10^{5.1}$ [CFU/g] and $10^{6.2}$[CFU/g] in the supercooled conditions and the refrigeration conditions, respectively. This means that the numbers of the bacteria are kept relatively at low level in the supercooled conditions. The number of bacteria after 3-week storages in the refrigeration conditions reaches to $10^{6.2}$ [CFU/g], which is higher than the safety value $10^{6.0}$ [CFU/g] described in the health protection agency reports in United Kingdom [20]. On the other hand, the ones in the supercooled conditions keep the safety level after 3-week storages.

5.1.5 CONCLUSIONS

A set of experiments are carried out to investigate the supercooled storages for the leaf lettuces produced by the plant factories. The followings are concluded:

(1) The freezing temperature of the leaf lettuces produced by the plant factories is around –0.2°C. The nucleation temperature of the leaf lettuces is between –1.0°C and –6.1°C.
(2) The type of the packages affects the characteristics of the supercooled lettuces by controlling the cooling rates in the supercooling processes. However, the additional packages increase the cost and the wastes, and it is required to consider the trade-off between the effects, and the additional cost and the waste.
(3) The lettuces under the supercooled conditions keep the initial characteristics of the water and sugar contents. The number of bacteria in supercooled condition is observed in low level against the ones observed in the normal refrigeration conditions. The number of bacteria reaches to the unsafety level after the 3-week storages in the refrigeration conditions.

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CHAPTER

5.2

Network and Processing System

Masashi Sugano

School of Knowledge and Information Systems, Osaka Prefecture University, Sakai, Japan

OUTLINE

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5.2.1 DATA COLLECTION BY WIRELESS SENSOR NETWORK

The efficiency of agriculture has increased through the use of information and communications technology (ICT), and plant factories will also be an appropriate setting for the application of wireless sensor networks [1–3]. By installing many sensors on large-scale farmland, and monitoring climate conditions, such as temperature, precipitation, and the amount of insolation, efficient farm management based on those data is performed in the United States. Particularly in recent years, the spotlight has focused on Farmlogs [4] as part of agricultural ICT ventures that supply agricultural network data and data integrated to grain market conditions. There are many uncontrollable conditions such as climate in either open farming or industrial cultivation, so data acquired using various sensors can be used for feedback control of farm management approaches. In contrast, a plant factory is equipped to control environmental conditions and maintain a particular cultivation environment, without being affected by the external environment. Thus, sensors and ICT can also be used to monitor environmental conditions and manage crop growth within a plant factory on a much smaller scale than such systems that are used in open agriculture [5]. In addition, as shown in Fig. 5.2.1, various communication methods with different communicable distances and different communication bands are in practical use. IoT became a reality by the communication method which is particularly low power consumption and suitable for small devices. By appropriately combining these, it is possible to monitor various data in the plant factory. (See Fig. 5.2.2.)

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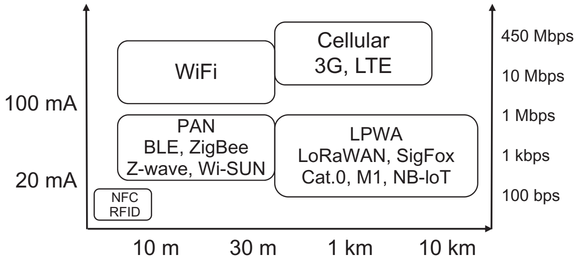

FIG. 5.2.1 Various communication methods and their characteristics.

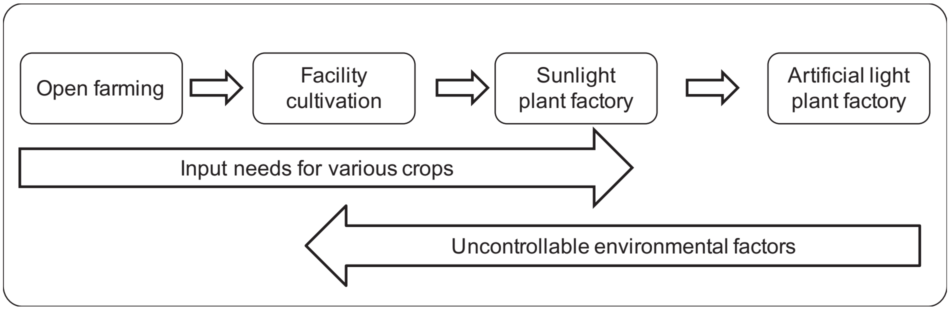
Open farming
Facility cultivation
Sunlight plant factory
Artificial light plant factory
Input needs for various crops
Uncontrollable environmental factors

FIG. 5.2.2 Differences in cultivation methods from the viewpoint of data utilization.

In a fully controlled, artificially lit plant factory, various data regarding temperature, relative humidity, culture solutions (EC, pH, and temperature), light intensity, air movement, CO_2, and other parameters are monitored by sensors, and these can be controlled to maintain appropriate cultivation conditions. This will allow the optimal cultivation environment to be maintained at lower cost. It is desirable to minimize the initial costs and to maximize the profitability of fully controlled, artificially lit plant factories. For that purpose, ICT is necessary not only for environmental control, but the data obtained by various sensors on the growth status of crops can be stored and analyzed. This data can then be used to construct models of the optimal cultivation conditions for each crop to reach its utmost potential.

5.2.2 DATA PROCESSING SYSTEM

Collection of high-precision data is required for constructing a database of optimal cultivation conditions. Further, the temporal and spatial intervals of monitoring should also be denser. In order to perform accurate climate control feedback by processing the stream of data generated from various sensors, real-time operation with complex event processing (CEP) is useful. A database that combines these environmental data with the crop growth data can be analyzed to generate the optimal cultivation model. Rather than a real-time operation, a data warehouse (DWH) is suitable for processing large datasets and extracting the best cultivation model. Then cultivation that is more efficient can be achieved by controlling the environment with reference to this optimal cultivation model. Fig. 5.2.3 shows such data flows.

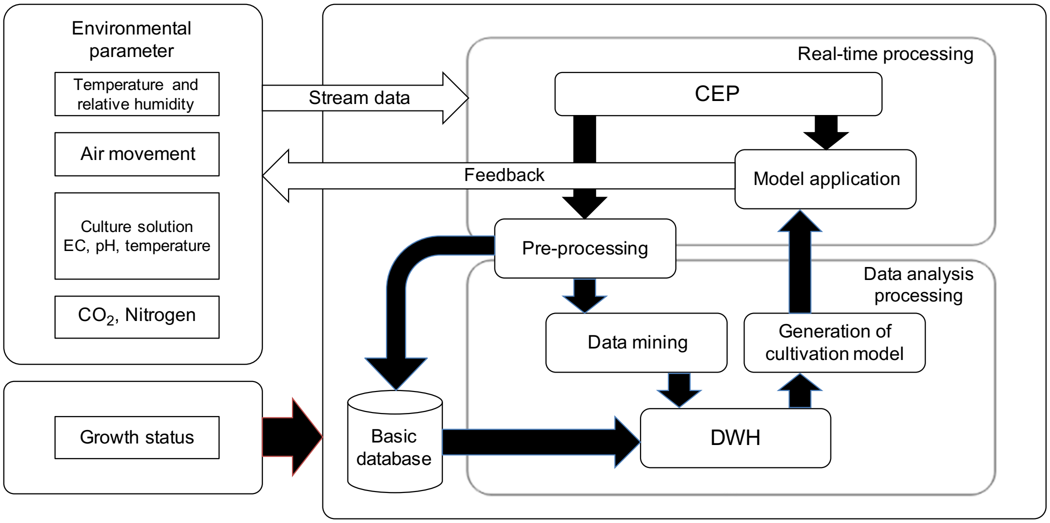

FIG. 5.2.3 Plant factory data processing system for realizing an optimal cultivation model.

Shortening the cultivation period of crops is not necessarily the only optimal route. This could depend on the type and timing of crops for their maximum commercial value, or could depend on when crops would have the best flavor or nutritional value. Therefore, in order to construct the optimal cultivation model, the data obtained and communicated should include not only environmental conditions in the plant factory, but also detailed data regarding the crops. It would be essential to consider and include which properties are valued in the market for that crop. Then the plant factory could always produce crops with higher added value at the lowest achievable cost.

5.2.3 CONCLUSIONS

This chapter describes the network for collecting data by IoT in a plant factory and the utilization of data by constructing a database. Here I mentioned data mainly related to plant development, but the scope of application of the database is not limited to it. By linking various data such as data related to logistics of produced crops and price data in the market, it can contribute to more efficient production of plants. The analysis method for big data which has made remarkable progress in recent years will be utilized in the production, distribution, and sale of crops by plant factories.

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CHAPTER

5.3

IT Networks and Plant Factories

Song Zheng

College of Electrical Engineering and Automation, Fuzhou University, Fuzhou, China

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5.3.1 BASIC REQUIREMENTS FOR IT SYSTEMS IN PLANT FACTORIES

Plant factory is currently the most advanced technology in the field of plant cultivation; plants grown in plant factories are not subject to natural conditions, and in the production mode and concept, such arrangement has completely outstripped the conventional meaning of agricultural production. The most prominent difference between plant and traditional agriculture is that the traditional agriculture depends on the planting staff to invest much labor in the natural environment for intensive cultivation. While the planting of the plant factory is carried out in a relatively confined and clean space for soilless cultivation, little or no manual work is required in the process. Therefore, it is necessary to rely on the advanced industrial technology. In other words, the most important prerequisite for creating the optimal environment for plant growth in plant factories, including the light, moisture, nutrient solutions and suitable temperature that the plants depend on, is the introduction of an efficient agricultural automation production system to save workforce and reduce production costs [1,2].

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Nowadays, the application of information technology (referred to as IT), including automation technology (referred to as AT), has become an important means of building a plant factory production system. Plant factories constructed in this way, even in the case of a large-scale, complex system, are managed and controlled more conveniently and flexibly than open farmland.

Like other industrial enterprises, the production process of plant factory needs some management and automatic control of the operation of related equipment to ensure that the quality and quantity of vegetable production conform to the factory design capacity requirements and meet the market demands. The basic needs of plant factory management and control involve the collection and monitoring of various environmental sensing data, the automatic control of greenhouse equipment, the detection of plant growth data, the production task management, packaging and logistics, and so on. These needs can all be met through the plant factory IT system with sensing, communication, control, and smart technologies as its core. Besides, the application of IT systems can also help plant factory to develop a better production plan and automatically adjust the best greenhouse growing environment. There is no difference in the hardware structure between the IT system of plant factory and the IT system of other production-type industries. The infrastructure of the production site is precisely managed and controlled through the computer. However, there are significant differences in software and algorithms that need to be adapted to the growth characteristics of different plant species. For example, a customizable growth control system can be designed within a plant factory to provide the optimal supply of growth elements for different plants, such as water, gas, fertilizer, temperature, light, and wind, depending on the differences and characteristics of the plant species. So each plant can root, sprout, and grow at the fastest and highest quality in the cultivation base. Furthermore, plant factory IT systems also have very strong demand for the application of artificial intelligence technology. Artificial intelligence can replace the human brain to observe, evaluate, and analyze plant growth processes and make optimal decisions on the improvement of IT systems. For example, an adaptive AI algorithm model can be designed and combined with a variety of environmental sensors and visual device. Then use it to judge the growth state of plants, including whether the luminance is sufficient, whether the color of the plants is healthy, whether the plant height and thickness meet the growth standards, and realize online adjustment of the control strategy for plant growth environment.

5.3.2 SYSTEM COMPOSITION AND TECHNICAL CHARACTERISTICS

Usually, plant factory IT systems are mainly composed of five subsystems: data acquisition and control signal drive, computer networks, data processing, process control, and human-computer interaction (HCI). Each subsystem has a specific function and role. They are interconnected to form an organic whole. Table 5.3.1 shows the functional description of each subsystem. As can be seen, IT network is the core component of plant factory IT system, but also the bridge of other subsystems' data connection. The deployment of IT network structure directly affects plant factory information collection, real-time processing and control, and other links.

TABLE 5.3.1 Functional Description of Each Subsystem of Plant Factory IT System

Subsystem	Description
Data Acquisition and Control Signal Drive	- Located on the device layer of the plant factory IT system, it consists of a large number of sensors, actuators, and corresponding drive equipment; - By a variety of sensors to collect a large number of closely related plant growth and environmental parameters of information; - Receive process control signals, drive the implementation of equipment, and regulate the corresponding environmental parameters.
Computer Networks	- Use of network equipment, line, and communication software to connect different I P, functionally independent plant factory subsystems, to achieve system resource sharing and information delivery
Data Processing	- The collected data information processing, sorting, calculation, into easily identifiable data types of HCI system; - The processed large amounts of data in an orderly storage, timely transmission through the IT network to the HCI system
Process Control	- Receiving control instructions configured by the HCI system and sending the instructions to the controller to complete the instruction operation; - Send the operation result of the control instruction to the device layer, and feedback the device status information to the HCI system in real time
HCI	- Develop rational management and control strategies for plant growth management, environmental monitoring, equipment control, and energy management, and generate corresponding control orders to the process control subsystem

A flexible IT network architecture is essential to building an efficient and low-cost plant factory IT system [3]. Fig. 5.3.1 shows the structure of plant factory IT network diagram. Plant factory environmental detecting sensors and execution devices can be connected to the corresponding data acquisition unit and controller through the IT network for data transmission and sharing. Monitoring and control of environmental conditions such as temperature, humidity, CO_2 concentration, and culture medium in cultivated greenhouses can be managed and configured by an HCI personal computer system. Humidifiers, ventilation equipment, fill-light devices and other functional devices can also be controlled by touch screen, tablet and other computer equipment to realize flexible control. It can be seen from the figure that the IT network of the plant factory can organically combine the automatic control part of the plant and the plant growth process management.

Fig. 5.3.2 is a typical example of a large plant factory IT network system. This represents a strongly coupled, high-cost IT network system. In this architecture, sensors such as light sensors, CO_2 sensors, thermometers, and hygrometers make up an environmental measurement system that can detect the status of a wide range of environmental conditions within a plant factory. Implementing devices such as heaters, chillers, LED fill-lamps, CO_2 supplies, air-blowers, and circulating pumps in the greenhouse and their coupled controllers become a system that performs independent functional operations. These sensing devices and executive devices access the HCI system through the gateway device. To realize the management and control of the entire plant growth process, the HCI system has set up different

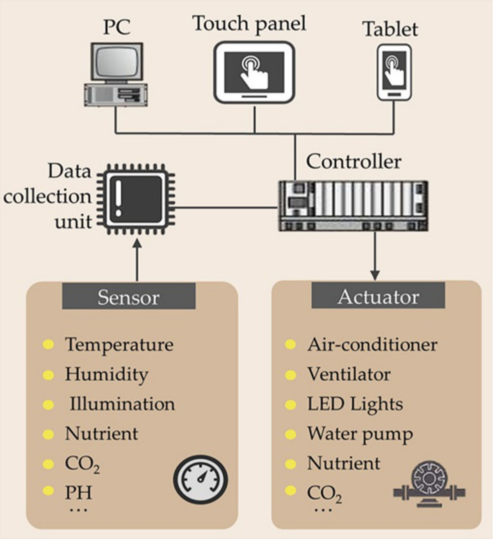


FIG. 5.3.1 Plant factory IT network structure diagram.

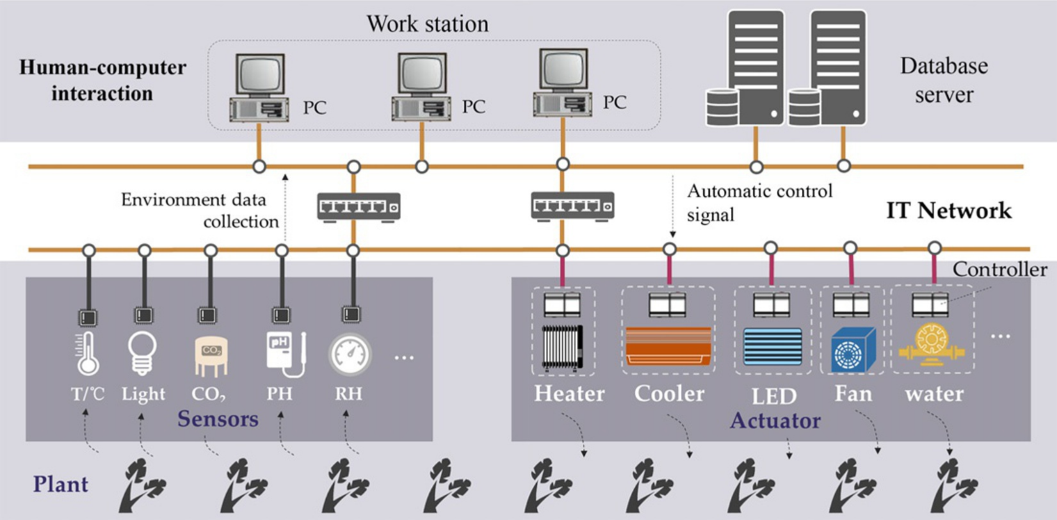


FIG. 5.3.2 Typical example of a strongly coupled plant factory IT network system.

workstations and data servers for the development and monitoring of system control strategies, as well as the storage and management of environmental detecting data and equipment operation data. The main feature of such a system is that it has a strong coupling, which means that the interfaces of different components and their functions and structures in the system are closely related. The software and hardware are self-contained, lacking the standards of network communication and algorithm control, and data management, system design and development costs are high. When the whole application or a part of it needs to be changed in some way, the functionality of the entire system can easily be affected to varying degrees.

Another plant factory IT network system is a kind of generalized network system. Fig. 5.3.3 shows a generalized IT network architecture based on the IAP control platform. As shown, the system features are configurable, visualized, and dynamic reconfiguration. Unlike the strongly coupled IT network system, the IAP plant factory IT network system deploys a common controller software (virtual controller) and intelligent gateway module at the control layer. It can unify management and transfer network-wide, compute, storage, and algorithms configuration and other resources, so that equipment hardware and software decoupling is done, and then achieve the heterogeneous device algorithm isomorphism purposes. The application software of IAP plant factory can be implemented using graphical configuration methods in a particular environment. Thanks to its reusable, visualized, and reconfigurable components, this approach allows plant factory applications to be developed more flexible and adapt to changing control needs. The IAP control platform is particularly suitable for use in plant factories where there are still many uncertainties in plant growth management and control.

No matter using strong coupling or common technology, the network is the most basic component of the plant factory IT system. Depending on the plant factory size, the number of devices connected to the network system also varies. Plant factories are the most typical industrial IoT applications, involving a large number of different types of sensing devices

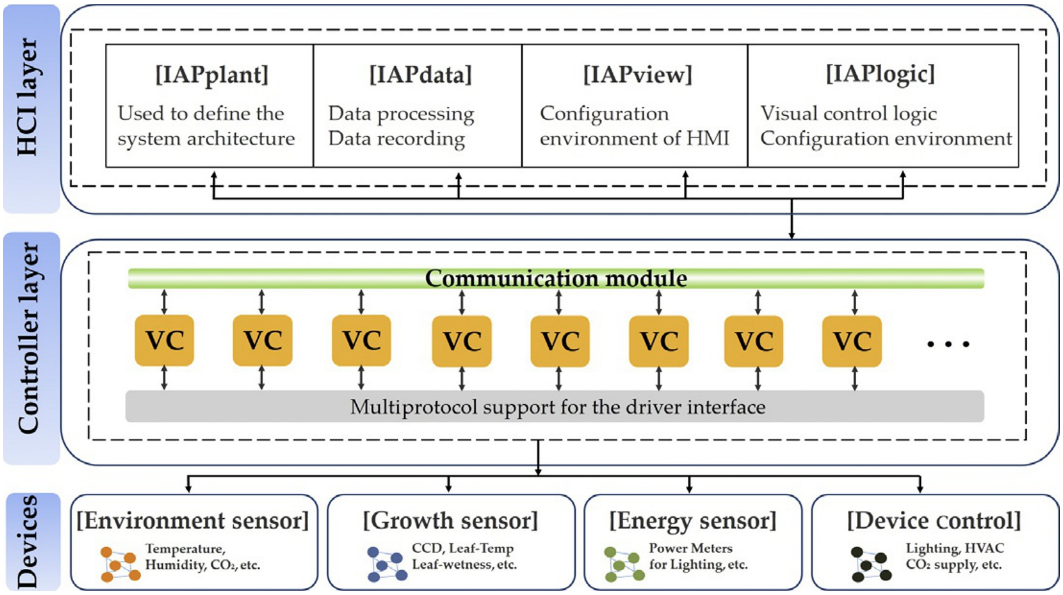


FIG. 5.3.3 IAP-based plant factory IT system architecture diagram.

and execution devices that require different communication protocols to be modulated for uniform data. Regardless of the type of control platform used, there are essentially no differences between plant management and control functions of IT systems. Both include online monitoring of plant growth environment data, the drive of plant factory control equipment, and measurement and processing of plant growth data (including the processing of image information), as well as the HCI setting of information management and automation control of plant factories.

5.3.3 PLANT FACTORY DATA COLLECTION

Data acquisition is the most basic function of plant factory IT network system. In large-sized and medium-sized plant factory IT systems, the amount of data collected is very large, but compared to other industrial IT systems, real-time requirements for data transmission are not high. Plant factory data collection and detection targets include environmental data such as temperature, humidity, light, the nutrient solution ion concentration, and other media information, as well as pumps, lights, air conditioners, and other equipment running status.

The sensor system belongs to the “sensory organ” of a plant factory. Its measuring principle is to convert specific environmental information in the plant growth environment into a detection signal that can be recognized by a computer. Sensors commonly used in plant factory include light intensity sensors, temperature sensors, humidity sensors, pH transmitters, conductivity transmitters, and dissolved oxygen controllers. Different types of sensors usually use different types of network protocols; their data communication mechanisms are also various, showing a significant heterogeneity. This heterogeneity makes each device’s applications to require careful configuration and custom programming, directly impacting greenhouse device integration and device interoperability. This phenomenon also exists in a large number of different types of execution devices.

At present, the data transmission of plant factory sensor mainly uses wired and wireless communication. The cable communication mode based on RS-485, Modbus and CAN bus and so on are characterized by high reliability and high anti-interference ability, but the wiring is multifarious. In contrast, the network structure of RFID, Zigbee, Wifi, Bluetooth, and other wireless communication can avoid the trouble of installation, provide more flexible management of monitoring points, and are more suitable for plant factories [4,5]. In recent years, the application of wireless sensor network technology based on the Internet of things to realize the dynamic perception of plant growth environment has become the research focus of plant IT network technology [6]. However, no matter using which way, the primary task is to deal with the heterogeneity of different networks.

Fig. 5.3.4 shows a method for designing the structure of wireless sensor network for plant factories. The sensor network of plant factory is composed of different terminal sensing devices, communication units, and data processing; these nodes form a distributed network structure through network protocols. The figure describes the topology of a clustered ZigBee sensor network, containing multiple end sensors, a few ZigBee routers that act as sensor parent, and the only ZigBee coordination node at the gateway device. The critical technology of

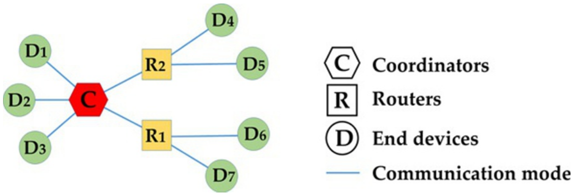


FIG. 5.3.4 The structure of wireless sensor network of typical plant factory.

the sensor network is to solve the problem of gateway data communication and processing, which can be seen from the figure.

Fig. 5.3.5 shows the data communication and data preprocessing diagram of plant factory gateway equipment. As shown, the gateway device is the core component of the data processing subsystem of plant factory, also known as gateway or protocol converter, and is a computer system or device that provides data conversion services between multiple networks. When a large number of sensors or execution devices use different network protocols, data formats, or programming languages, the gateway device acts as a "translator" that needs to repackage the received messages to meet the data management needs of the system. When a large number of heterogeneous sensing devices exist in plant factories, the data collected at the site is uploaded to the HCI system only after pre-processing in the gateway, so as to save communication resources. From this perspective, the gateway cannot be completely classified as network hardware, but can be summarized as software and hardware products that can connect different networks.

Fig. 5.3.6 shows an example of a typical sensor network communication. This case describes how to connect multi-protocol-based multi-sensors and devices through a gateway device. In this case, the control station is configured with a common gateway equipment, the internal integration, an ARM controller, and a multi-protocol driver interface and supports ZigBee, Wifi, Bluetooth, infrared, and different network protocols such as Modbus, CAN bus and so on. When the system is working, sensors such as temperature, humidity, and PH can communicate with the gateway device separately through their communication modules or their parent nodes (such as ZigBee routing). The controller of the gateway device can receive real-time values from different sensors through a uniform device driver interface and perform corresponding data processing operations, and then transmit the specified parameter values to the water sprays (actuators) to drive the nozzles to execute the necessary spray water operation.

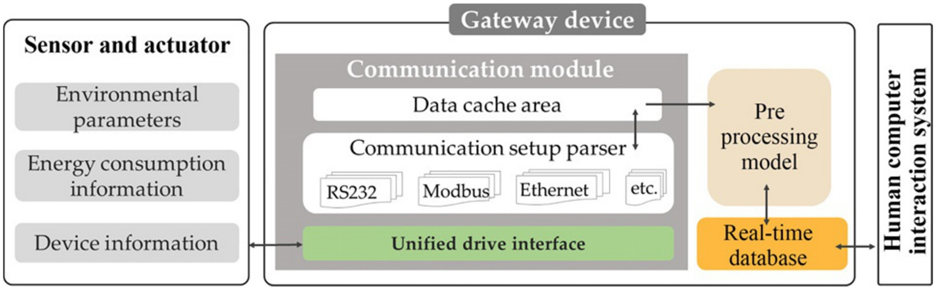


FIG. 5.3.5 Plant factory gateway equipment data communications and data preprocessing diagram.

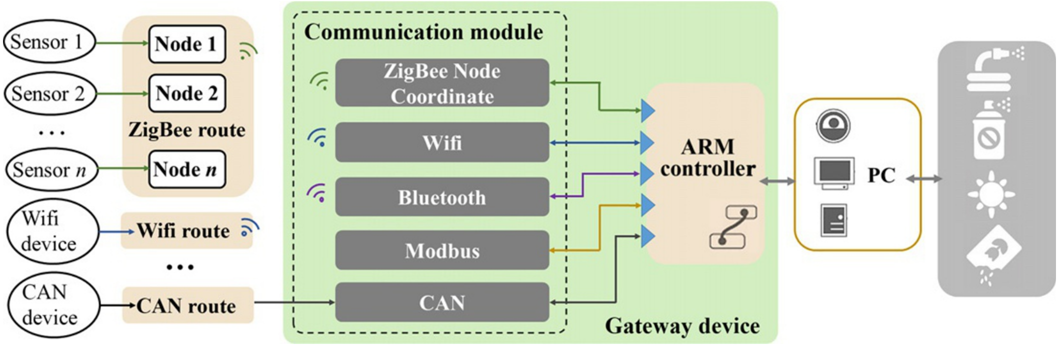


FIG. 5.3.6 Schematic diagram of data communication and data pretreatment of plant factory gateway equipment.

5.3.4 AUTOMATIC CONTROL STRATEGY

Automatic control is the most important component of the plant factory IT network system, which is embedded in the IT network system. The goal of automatic control includes three aspects. One is to control the environmental status of the plant factory so as to meet the needs of plant growth dynamically. The second is to keep track of the energy consumption, growth cycle, and plant appearance of plant factory, incorporating it in the production status of the most energy saving, best quality, and fastest supply and demand. The third is to realize the production process control and production management of data, to meet the factory management (harvesting, packaging, logistics, etc.) and highly collaborative production technical requirements.

Taking the IAP control platform as an example, to realize these three goals, the virtual controller of the IT network system needs to be configured to form a multi-loop information control system. Fig. 5.3.7 is the schematic diagram of multi-control loop structure of automatic control subsystem of the plant factory. Regarding automatic control section, the main control loop includes the control of environmental temperature and humidity, CO_2 concentration

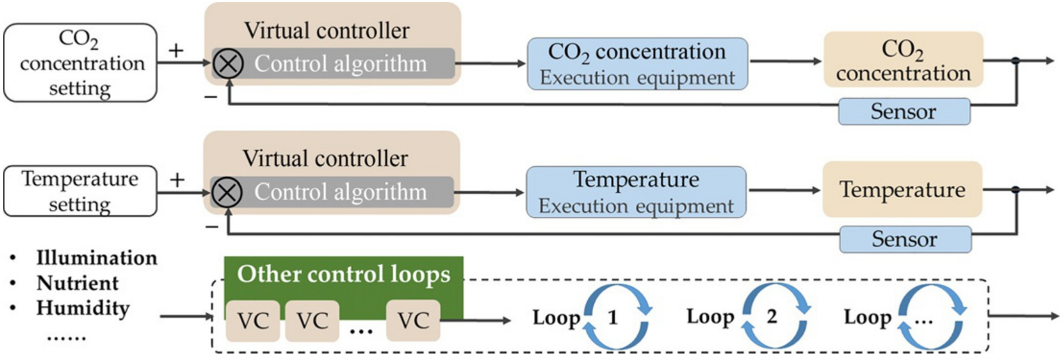


FIG. 5.3.7 Plant factory automation control subsystem multi-control loop structure diagram.

control, environment auxiliary light source wavelength control, detection of nutrient solution and automatic control, etc. Temperature control loop is the use of heating, ventilation, cooling and water mist, and other ways to adjust the ambient temperature so as to get the most suitable temperature for the growth of plants. Auxiliary light source control is based on plant species, and the demand in different growth stage light environment adjusts the light source device, makes its output wavelength of light, luminous intensity, luminous parameters such as frequency, the spectral ratio at the optimal state of plant growth. By measuring nutrient solution EC, pH, DO, and liquid temperature and other parameters, nutrient solution detection and automatic control will allocate the concentration of nutrient solution and timing of providing the liquid, to meet the production needs of the plant. The power of CO_2 concentration is based on the growth characteristic of the target plant to adapt to the CO_2 concentration of its growth; the basic principle of the control loop is to read the real-time value of the sensor from the CO_2 sensor and compare it with the set threshold. If the detected concentration is lower than the threshold, open the CO_2 valve; on the contrary, close it.

In the IAP control platform, all the algorithm configuration of the control loops are completed on the terminal equipment of HCI system. Fig. 5.3.8 gives the local logical graph and its dynamic characteristics of the intensity control of plant growth light. As can be seen from the diagram, the control loops of the automatic control subsystem of plant factory can be realized by using reusable components such as HLM (High and low alarm), T (latch), AND, OR that follow a specific connection. Also, the component calculation process of the entire control loop is dynamically visible. With the help of the trend chart tool of HCI system, the operator of the factory can also monitor the change of each environmental parameter and monitor the execution of each control instruction dynamically.

To improve the plant production efficiency and quality, reduce energy consumption, and save the cost of the economy, it is necessary to optimize the management and control strategies of the production line in time, especially large-scale plant factory. For many IT systems already in production, to ensure stable production, modifying the control strategy often means the shutdown of the partial production system. Reconfigurability is a crucial indicator to evaluate whether the IT network system of plant factory is open and robust, which involves system control logic (algorithm), and control parameters can be optimized and adjusted

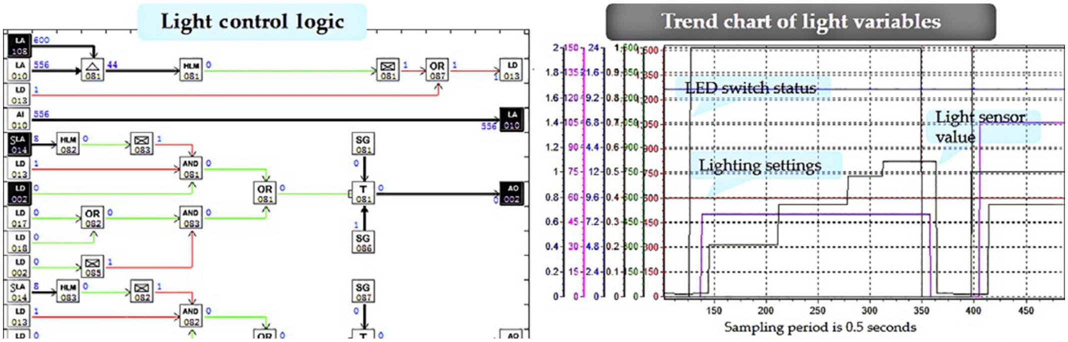


FIG. 5.3.8 The local logic diagram of light intensity control loop of typical plant factory and its dynamic characteristics.

online. Dynamic reconfiguration technology is a reliable method for online optimization of plant factory IT systems. It can update the algorithm model inside the controller software without disturbance under the condition of normal operation of the controller. Taking the wavelength control of the auxiliary light source in IAP plant factory as an example, the principle of its control circuit is based on the different light levels between day and night, the lighting system with multiple LED bulbs, and the timer used to operate the light source. But in this way, the light conditions obtained by plants are not ideal, and the energy efficiency is low. To realize the adaptive control of plant growth, a new control loop can be designed by using the method of component configuration. The new loop takes the environmental data of the spectrometer as input, such as real-time wavelength, color temperature, red/blue/green ratio, etc. And combined with changes in the real-time value of day and night light intensity, it automatically adjusts the LED fill-light device red/blue/green ratio and its light output, making it the best lighting condition for plants. When the control strategy is switched, it only needs to use the software online processing module to configure the optimized configuration program to the virtual controller; this process does not have a big impact on the operation of the system control loop.

Regarding operation and maintenance, the plant factory's IT network system can be designed for automatic, semiautomatic, and maintenance operation. Automatic operation means that part of the factory production processes is completed by the automation equipment and does not require any human intervention, especially germination, nursery, planting and other plant growth monitoring, control, packaging, logistics, and other processes. Although some advanced plant factories IT systems have been able to achieve collaborative docking of production control and management, there are still some applications mainly based on the automatic system operation, supplemented by manual control; especially in the control link that has certain dependence on artificial experiences, such as production planning and quality testing. Also, with the application of plant factory IT system, people's dependence on information management and control systems has also increased. The operation and maintenance of the IT system are necessary; this work mainly involves system status diagnosis, fault repair, big data management and maintenance, and online optimization and analysis prediction of production strategy. The above three modes of operation exist in most large and medium plant factories. However, with the development of IT network technology, the IT system of plant factory will inevitably evolve toward full automation and intelligent direction.

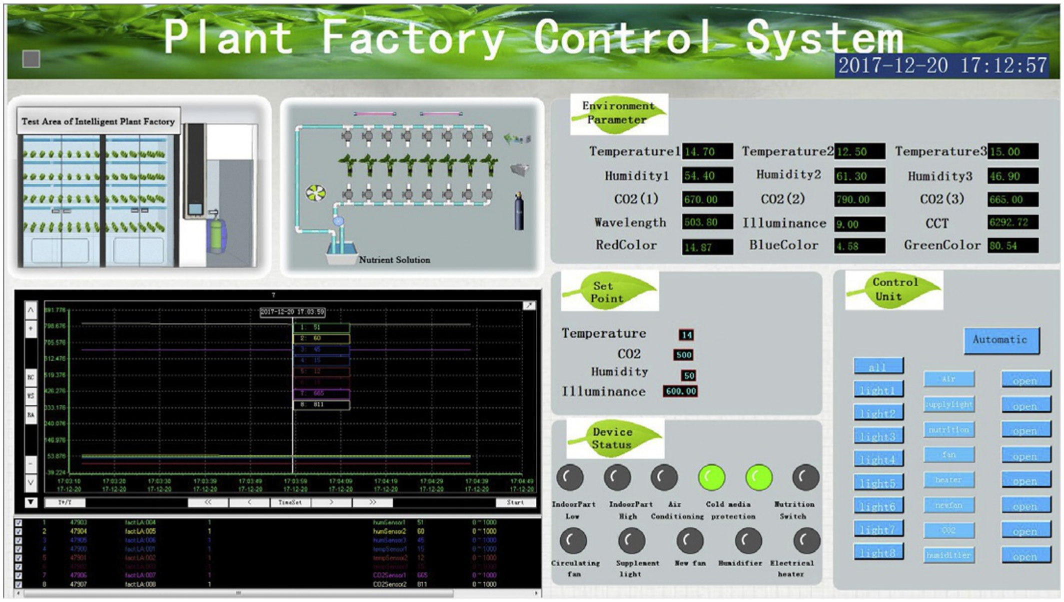
5.3.5 HUMAN-COMPUTER INTERACTION TECHNOLOGY AND ITS APPLICATION

HCI is an important part of the software of plant factory IT network system, and the whole IT system can be completed in the HCI system. In general, the HCI software consists of three parts: system definition, human-machine interface (HMI), and algorithm design. System definition refers to the internal configuration setting of IT network system, including control station, data structure, and data communication. The human-computer interface is the software tool for production managers to monitor plant factory. Algorithm design is an algorithm editor that can be used to design or monitor an IT system. The relationship between algorithm design and system definition software is to load control algorithm configuration data to the controller or monitor specific configuration elements. The relationship between HMI and system definition software is to extract the data information required by the HMI or download control instructions to specific controllers. HMI and algorithm design are interconnected through the data channels configured by the system definition software, and the three are configured together to form a complete plant factory IT network software system.

Taking the IAP control platform as an example, these three types of software are characterized by their instrumental nature. Different management or control applications of plant factory can use the same tools. Their application requirements are not satisfied by the software tools themselves, but by the configuration elements inside the tools. Configuration and composition of configuration elements (topological results) can determine the function and performance of the IT network system. In the design and development of the plant factory applications, only through the HCI software tools its internal components are operated, forming the corresponding configuration model, and configured to the virtual controller to perform, and ultimately meet the system management or control requirements' purpose.

Specifically, the system design software has a unique template that is configured for each device, and the input and output signals and their data relationships are defined. The status of all control objects, such as plant factory sensors or execution devices, can be managed as device properties. When the system is developed, it just needs to call the corresponding template and associate it with the specified controller. And the editing, linking, loading, and monitoring of the control loop algorithm are done in the algorithm design software. Algorithm design software can use the form of a drawing for the design and edit of control algorithm visually and also provides monitoring environment and the trend of dynamic interface for the visualization algorithm implementation process, which is very useful for analyzing and predicting the dynamic characteristics of the control algorithm, especially the reconstruction of the dynamic configuration function, and can continuously update the control algorithm under the premise of normal operation of the controller, which is of great significance for performance testing and online optimization of the algorithm. With HMI software, operators can monitor plant factory production processes in real time (including operation); IT system alarm and video monitoring are also completed in this software. Fig. 5.3.9 is an example of the plant factory human-computer interface showing the plant growth status settings and monitoring options in the experimental area. A HMI in the figure shows the current state of plant factory, including the light color and intensity, plant factory environment temperature, humidity, CO_2 concentration, and the actuator switch status, such as refrigeration units, heating units, dehumidification mechanism, humidification, and solenoid valve. The operators can remotely modify the setting parameters of the controller.

Also, the production and operation data of plant factories are all stored in IT systems, which can be used for production management backtracking. One can find statistics at any time in the man-machine interface, for example, the light intensity, indoor temperature, humidity, CO_2 concentration, as well as the maximum, minimum, average of the whole month, all week, full day, and a period of time; draw the illumination intensity, indoor temperature,



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Temperature1 14.70
Temperature2 12.50
Temperature3 15.00
Humidity1 54.40
Humidity2 61.30
Humidity3 46.90
CO2(1) 670.00
CO2(2) 790.00
CO2(3) 665.00
Wavelength 503.80
Illuminance 9.00
CCT 6292.72
RedColor 14.87
BlueColor 4.58
GreenColor 80.54

Temperature 14
CO2 500
Humidity 50
Illuminance 600.00

FIG. 5.3.9 Part of the screenshots of the HMI of plant factory: Local area plant growth light setting and monitoring screen.

humidity, and CO_2 concentration at any time. It can also be used for the analysis of various production performances, including the potential relationship between plant growth status and environmental factors so that the plant can grow rapidly in a more suitable environment; analyze the relationship between production management plan and plant growth quality and output; and evaluate the operation status of the equipment and diagnose and warn the production process.

5.3.6 APPLICATION OF CLOUD PLATFORM IN PLANT FACTORY

With the rapid development of IT technology and its penetration into agriculture, the plant factory industry is evolving toward a large-scale and intelligent direction [7]. In particular, the technology of cloud computing in recent years has also provided a new technological approach to the application of plant factory IT systems. Especially in recent years, the rise of cloud computing technology has also provided a new technological approach to the application of plant factory IT systems. The concept of cloud plant factory was also proposed; it refers to a class of advanced technologies such as embedded, sensor, wireless communication and intelligent logistics, and with cloud platform as storage and computing center. If smart hardware is the "body" of a plant factory, the software is "skeleton," and the IT system is a "meridian," then cloud computing is where the brain of the plant factory is located. Therefore, this transformation of plant factory is very important.

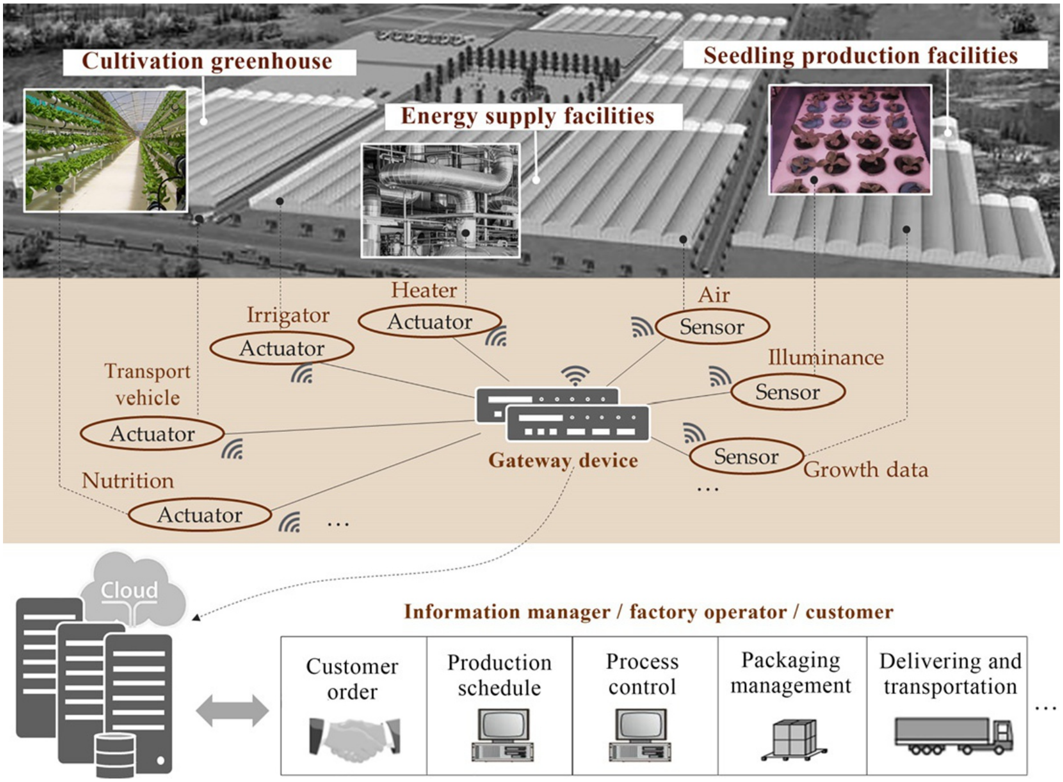

FIG. 5.3.10 An overview of the cloud plant factory.

As shown in Fig. 5.3.10, plant factory itself is a class of complex large-scale system that in the future will need more intelligent devices, including a variety of functional diversity of robots and sensors, which will produce a lot of information to be processed. It is a new direction to hand over complex information processing problems with cloud computing [8]. In this way, people can manage the production process of plant factories through the Internet, including product sales. In other words, plant factory orders, management of production orders, production planning, plant growth control, processing, and logistics can all be monitored and controlled at remote terminals.

At present, the development of many new technologies in this field already has the condition of engineering application. Fig. 5.3.11 is a schematic diagram of a cloud plant factory based on IAPcloud. As can be seen from the figure, the structure of the cloud plant factory can be divided into the edge system, cloud platform, and HCI system. The edge system consists of a large number of sensor/sensing devices, execution devices that control environmental factors, and controllers and network devices for edge data processing. The HCI system is composed of HCI software that can be connected to the Internet. It can access cloud platform data resources remotely and monitor plant growth management and control process in the edge system. From the perspective of demanders, cloud platform provides the data forwarding,

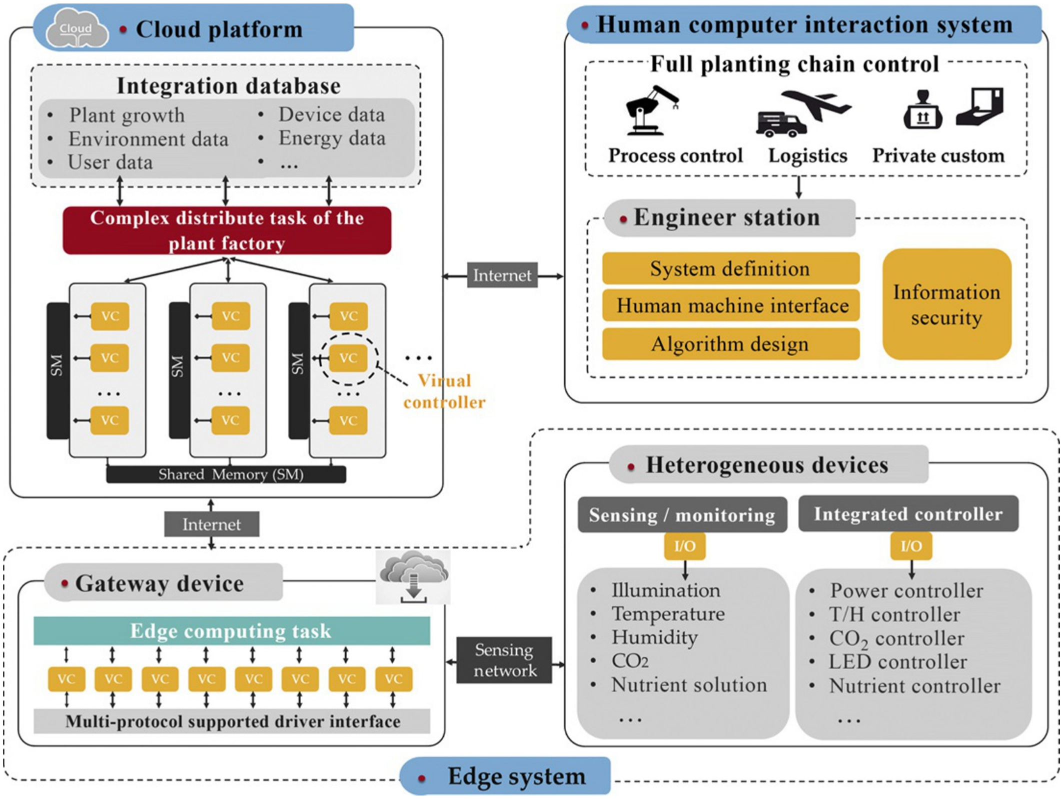

FIG. 5.3.11 Schematic diagram of cloud plant structure based on IAPcloud.

storage, and computing functions that are accomplished by many virtualized server farms, including computing servers, storage servers, and bandwidth resources. In general, producers and consumers only need to rent these servers on demand to get the resources they need. The biggest difference between cloud plant factories and traditional IT systems lies in the application of cloud computing environment and the Internet. These two technologies also create great space for the development of plant factory IT systems and the transformation of business models. First, all the data collected by the edge system will be uploaded and stored in the cloud. The cloud platform provides plant factories with a greater number of remote controllers for real-time computing and finer control. Second, cloud platforms can integrate more heterogeneous devices into one system; even industrial, the ones on the industrial chain, without being affected by geographical location. Besides, the cloud platform is more suitable for the applications of big data technology that require a large amount of computing, including the analysis of plant growth status based on big data, user consumption data analysis, and personalized production and customization of the product. In the future, consumer demand for plant factory products becomes predictable, and the product ordering, production process status, and information feedback are all accessible to producers and consumers over the Internet.

The advantages of the cloud plant factories are obvious. However, with the development of new technology and industry and change, the technology will also face new challenges, for example, the reliability of the cloud platform and its information security problems. Cloud platforms provide remote access to the plant factory. Adopt cloud platform means that data and applications need to be distributed across multiple data centers; it needs to create new security boundaries, require more protection against attacks, and ensure factory and user data security. If a cloud service provider suffered a serious virus attack, it is bound to cause damage to the service network. This is equivalent to "brain" of the plant factory eroded, causing the entire factory to lose control and cause serious economic losses.

However, as a general trend of the development of the entire industrial civilization, the adoption of cloud plant factory production methods is irreversible. Cloud plant factory will pay more attention to the application of artificial intelligence technology due to its strong cloud computing power. For example, through image or video information processing of the plant growth, combined with historical data analysis of plant factory equipment operation, the precise model of the growth process of different kinds of plants was established, and the technical conditions were provided for the optimal growth state of the plant. In the meantime, with the development of Internet of Things (IoT) technology, in the future, every item in a plant factory may have its own unique label that needs to be transmitted to the cloud platform to participate in the processing of business logic, all of which will be done through cloud computing achieve. Using the extensibility of cloud platform, the on-demand expansion of computing, the storage, and network resources will become an important means of plant factory construction in the future.

5.3.7 CONCLUSIONS

Given the basic needs of IT systems in plant factories, this paper discusses the importance and necessity of deploying IT systems in plant factories and proposes the plant factory definition and composition framework based on IT systems. In contrast to strongly coupled IT systems, this paper focuses on the generalized IT network architecture based on the IAP control platform to analyze the advantages, features, and applicability of the generalized IT system regarding the configurability, visualization, and dynamic reconfiguration. In the face of a large number of different types of sensing devices and execution devices, a typical example of the sensor network communication is presented. It introduces how to connect multiple types of sensors and devices with different communication protocols through common gateway devices to obtain unified data management so as to achieve the system management and control. On this basis, we further explain the major operations of the whole production process including the template setting of sensors, production process monitoring (including operation), the editing, connection, loading, and monitoring of the control algorithms.

The main contribution of this paper is also put forward: the concept and architecture of the cloud plant factory and its design principle and analyses of the advantages of this architecture in the integration of plant factory heterogeneous equipment, the data management, and the visualization of control strategies based on the cloud IAPcloud plant factory. It shows that the future cloud platform can integrate more heterogeneous devices into one system, even the industrial equipment on the industrial chain, and not be affected by the geographical location.

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PART III

VARIOUS TECHNOLOGICAL APPROACHES AND BUSINESS STRATEGIES FOR PLANT FACTORIES

CHAPTER

6.1

Fundamental Components and Points to Consider in the Design of a Plant Factory: An Example of OPU New-Generation Plant Factory

Teruo Wada[*], *Hirokazu Fukuda*[†], *Toichi Ogura*[‡]

[*]Graduate School of Life and Environmental Sciences, Osaka Prefecture University, Sakai, Japan
[†]Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, Sakai, Japan [‡]Sanshin Metal Working Co. Ltd., Osaka, Japan

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6.1.1 INTRODUCTION

The Osaka Prefecture University's Research and Development Center for Plant Factory (PFC) was established in 2011. It is one of 13 research centers adopted as development projects for research and development of plant factories by the Ministry of Economy, Trade and Industry (METI) or the Ministry of Agriculture, Forestry and Fisheries (MAFF). Osaka Prefecture University was adopted by both ministries. PFC is the only center specialized for the

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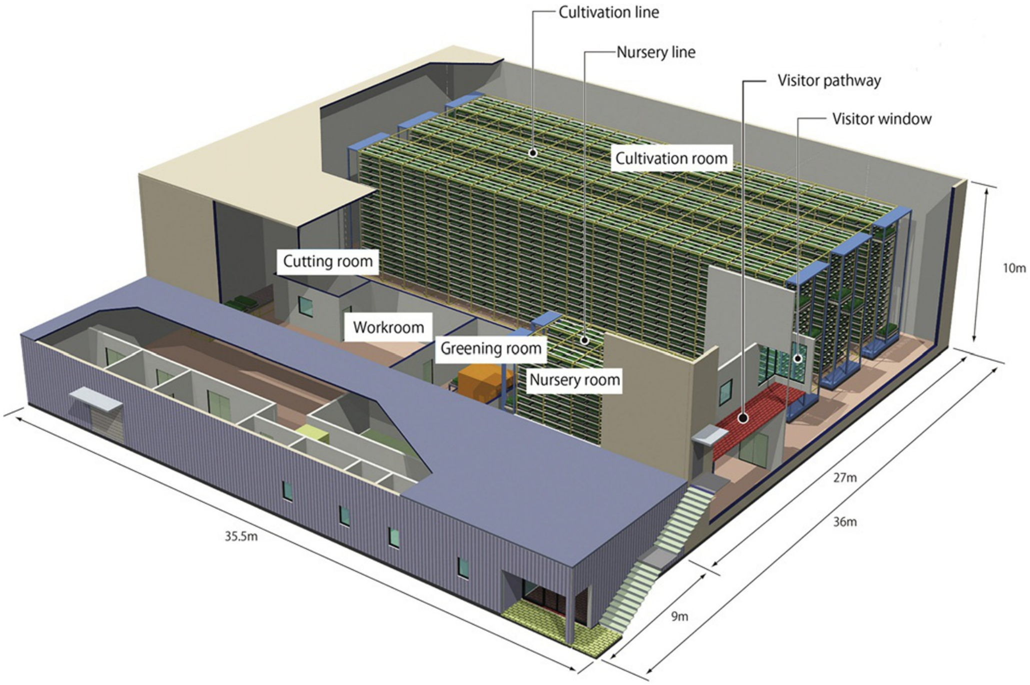


FIG. 6.1.1 Green clocks new-generation plant factory.

plant factory with fully artificial lighting in Japan, and we are working on research and development as well as expansion of technology with a consortium of about 80 companies. The center also established the New-Generation Plant Factory (GCN), which is a large-scale plant factory producing 5000 lettuce plants per day using Green Clocks Technology through the financial support of METI (Fig. 6.1.1). In this plant factory, empirical research is being conducted for (a) automatic system selecting good seedlings using Green Clock Technology (Chapter 6.2), (b) reduction of labor cost by an automatic transporting system, (c) reduction of energy costs using light emitting diodes (LEDs) as light sources, (d) standardization of the plant growth environment by a direct air-blowing system, and other efforts [1]. Based on these experiences, fundamental systems and points to consider in the design of a plant factory with fully artificial lighting will be introduced in this chapter.

6.1.2 FUNDAMENTAL SYSTEMS AND CONSIDERATIONS IN THE DESIGN OF A PLANT FACTORY

In a plant factory with fully artificial lighting, all component systems including the growing beds and solution circuit in the hydroponic system, multilayer racks, light sources, air

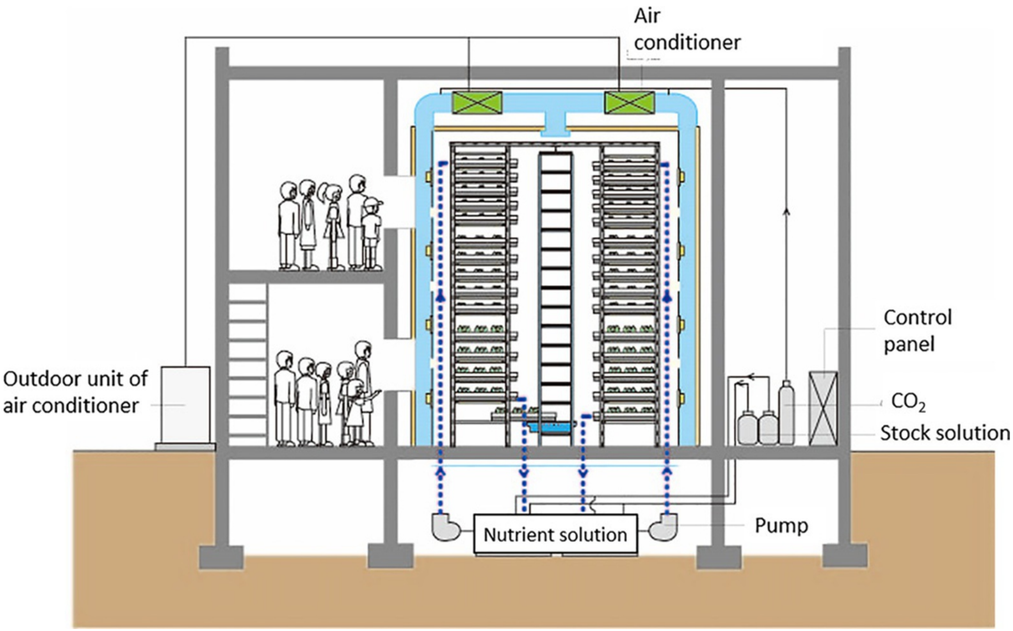


FIG. 6.1.2 Schematic model of plant factory.

conditioner, and transport system are installed indoors. As an example of a plant factory, a schematic of a lettuce production room in our center is shown in Fig. 6.1.2. The fundamental systems are described below.

6.1.2.1 Cultivation System

The cultivation system is one of the most important systems and includes hydroponic beds, multilayer racks, the solution circuit, and light sources. Their specifications will be determined based on what plants and how many are to be grown in it.

6.1.2.1.1 Hydroponic Beds

Hydroponic beds can be considered analogous to soil in an open field. They supply water and nutrients to the plant roots and structurally support the plants. In a plant factory, hydroponic systems without any soil are used because they support faster growth, avoid injury from continuous cropping, prevent contamination from soil or sand, and are suitable for mechanization, in addition to other considerations. These advantages fit the aim of a plant factory of producing very safe vegetables in short growing periods under clean conditions. The major hydroponics systems rely on either the deep flow technique (DFT), in which the nutrient solution is pooled to several centimeters in the beds and flows in the beds or the nutrient film technique (NFT), in which the nutrient solution is not pooled and only flows through the beds at a depth less than a few centimeters. The DFT system is the most popular in the plant factories in Japan. DFT beds are assembled from molded polystyrene forms

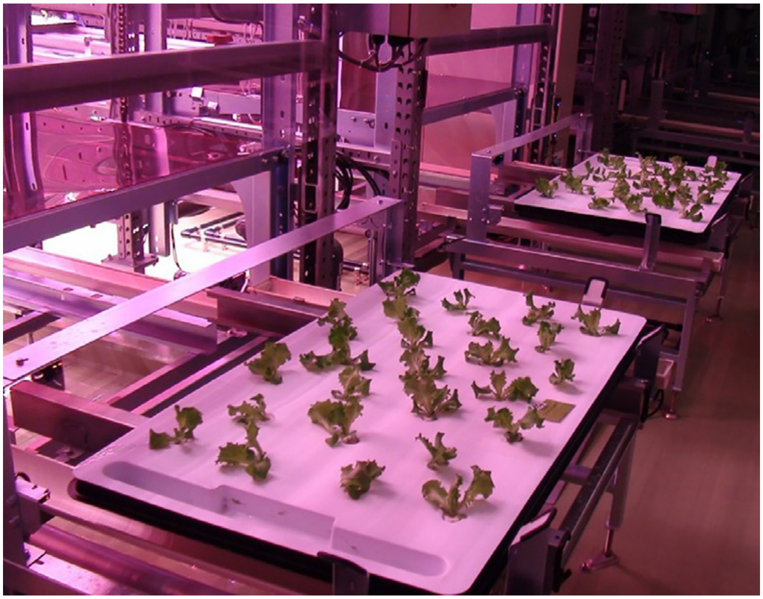


FIG. 6.1.3 Molded plastic bed of NFT system.

covered with polyethylene sheets to keep the nutrient solution at a 3–10 cm depth in the beds. Polystyrene planting panels, where seedlings are transplanted to, float on the solution. The length of a bed is 20–30 m. It is easy to make the beds and to move planting panels from one end to another of the beds because the panels are not fixed to the beds. However, the DFT beds are heavy because of the amount of held nutrient solution, so they need stronger shelving. When the length of the beds is longer, a higher flow rate of the nutrient solution or aeration system is often needed to prevent a decrease in the amount of dissolved oxygen. In contrast, NFT beds can be assembled either in a similar way to DFT beds or as a combination of small separated beds with a length of 1–2 m. Though a 1%–3% incline is needed to allow the nutrient solution to flow in long beds, no incline is needed when the bed length is shorter than about 5 m. In the GCN, an NFT system with small separated beds 1.2 m long (Fig. 6.1.3) was installed. The molded plastic beds that are originally designed have higher cost, but they also have advantages such as ease of washing and disinfection of the beds after each harvest, suitability for an automated transporting system, and lower bed height, which accommodates more layers of shelves for the same ceiling height. An alarm system that sends an alert when irrigation stops was also installed because plants in an NFT system wilt quickly when irrigation is interrupted.

6.1.2.1.2 Multilayer Racks

One of the advantages of a plant factory with fully artificial lighting is enabling multilayer shelves. The system described in Fig. 6.1.2 holds 15 shelves in a 7 m high room. The GCN has 16 or 18 shelves in a 9 m high room. The 16-layer shelves were designed to grow plants taller than lettuce. The number of shelf layers is determined by the height needed between shelves.

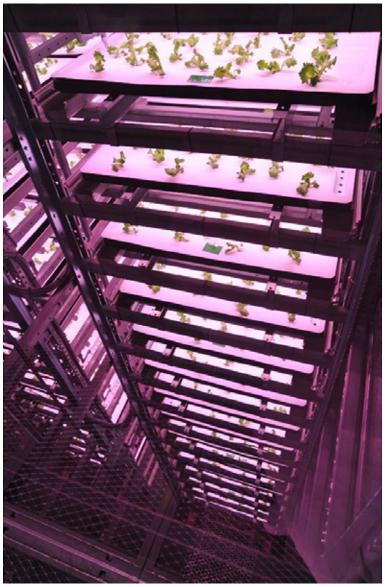


FIG. 6.1.4 Multilayer rack.

In one shelf interval, a hydroponic bed, light source, and shelf construction materials have to be installed and still accommodate the height of the plants to be grown. The shelf interval thus depends on what materials or systems they will be used for. In the GCN, an assembly rack with a weather-resistant steel plate, LED lighting unit, and movable NFT beds with an automated transporting system were adopted, and the height of lettuce plants was assumed to be 20 cm based on examination of plants with 90 g fresh weight, which is a general harvest size. This allowed determination of the interval of the shelves as 40 cm. Therefore, 18-layer shelves could be installed into the 9 m high room, as shown in Fig. 6.1.4. Because dew condensation occurs during the dark period in a plant factory, and fertilizer salts are included in the nutrient solution, the racks must be made of materials with corrosion resistance. Resin-coated steel or aluminum extrusion mold products are sometimes used for racks. Attention must be paid to the reduction of the construction period and ease of maintenance in addition to earthquake-resistant strength and load capacity for hydroponic beds including the nutrient solution, lighting system, and plants.

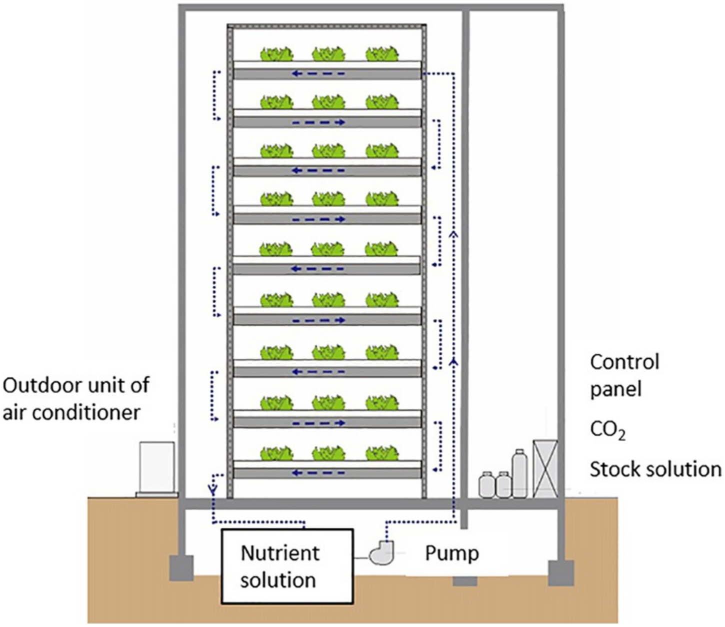
6.1.2.1.3 Solution Circuit

In the GCN, a DFT system was installed for raising seedlings in the nursery room. An NFT system is unsuitable for raising seedlings because plants roots become entangled and form a root mat, making transplanting difficult. There are two lines of the DFT system in the nursery room, and each rack has 15-layer growing beds 1.2 m wide and 9 m long. The nutrient solution is supplied from one end of the beds with an aeration system and flows in the beds, and the liquid that drains from the other end of the beds returns to an underground solution tank. The flow rate of the nutrient solution to each 15 beds in the line is 25 L min^{-1}, and total flow rate of the line is 375 L min^{-1}. The volume of the solution tank is 7000 L. The volume of the tank should be designed such that the solution will not overflow when the pump is stopped and the water level remains at about 50% of the tank volume when the pump runs (regular operation mode).

In the cultivation room, an NFT system was installed because an automated transporting system that transports each NFT bed with plants was adopted. Assuming that the growing period in the cultivation room is 18 days and the plants in two beds on every shelf are harvested every day, one shelf must have 36 beds in a 30 m length. The nutrient solution has to be supplied to every 36 beds simultaneously. Assuming that the flow rate of the nutrient solution to each bed is 3 L min^{-1}, the flow rate in one shelf with 36 beds will be 108 L min^{-1}. The GCN has six racks, which have 16 or 18 shelves each, and one solution circuit controls the nutrient solution for two racks. If each rack had 18 shelves and the nutrient solution was supplied to all beds in two racks simultaneously, the number of shelves of one solution circuit would be 36 and the total flow rate of one solution circuit would be about 3900 L min^{-1}. This value is not realistic, because too big a pump would be needed. Actually, the shelves in a rack are divided into upper and lower parts. In each part, the nutrient solution is supplied to the top beds, sequentially goes down to the next-lower bed, and then goes back to the solution tank after flowing through nine beds. Furthermore, irrigation is alternately provided to one of two racks at 1-min intervals. By this operation, the flow rate of one solution circuit can be decreased to 1/18. In this operation, the location of the irrigation port and drain port of each bed alternates every shelf, as shown in Fig. 6.1.5. Fail-safe manuals are needed to prevent worker confusion.

Attention should also be paid to the source water used to make the nutrient solution. Rain water, well water, and tap water are usually used as source water. When well water is used,

FIG. 6.1.5 Schematic model of solution circuit of multilayer rack.



analysis of mineral concentration and check for coliform and other bacteria before use and periodically after should be carried out. Sometimes, demineralization or sterilization will be needed [2]. When tap water is used, removal of chlorine is necessary before use. Chlorine is converted to chloramine, which is very toxic to plant roots when it combines with ammonium ion in the nutrient solution. In order to remove chlorine from the water, sometimes the water is kept in an open tank for a few days or a reducing agent such as sodium thiosulfate is added [3]. In the case of the GCN, tap water is used as source water for the nutrient solution, since a dechlorinating filter has already been installed. The quantity of water needed for plant growth is related to the transpiration rate, except at renewal of the nutrient solution. We think empirically that evaporation in excess of the transpiration rate is minimal in a plant factory. In the cultivation room of the GCN, plants at 20–38 days after seeding are grown and the averaged water consumption of these plants is estimated to be about 50–60 mL $\text{plant}^{-1}\,\text{day}^{-1}$, depending on cultivar. Thus, the water consumption of one solution circuit with 32,400 plants is estimated to be around 2000 L day^{-1}. Each solution circuit has a 7000 L tank, and it is estimated that solution volumes during operation are approximately 3500 L in the tank and 2500 L in beds and pipes. The water consumption is always monitored and that value would be one of the indicators of the normality of plant growth.

The nutrient solution is mixed by an automatic fertilizer with monitoring of the EC and pH value of the solution. However, calibration of the sensors and analysis of the mineral concentration of the recirculating nutrient solution must be carried out periodically.

6.1.2.1.4 Light Source

It is thought that light requirements of plants are 100–300 μmol $\text{m}^{-2}\,\text{s}^{-1}$ of photosynthetic photon flux density (PPFD) for leafy vegetables, 200–600 μmol $\text{m}^{-2}\,\text{s}^{-1}$ for fruiting vegetables, and 50–200 μmol $\text{m}^{-2}\,\text{s}^{-1}$ for ornamental plants [4]. One of the reasons why leafy vegetables are grown in plant factories is a lower light requirement, about 200 μmol $\text{m}^{-2}\,\text{s}^{-1}$. Though the light source in plant factories was high-intensity discharge lamps in the 1990s, fluorescent lamps had become popular in the 2000s because multilayer cultivation could be realized by close irradiation. Since 2010, LEDs, which have the property of low energy consumption, are becoming the most popular light source in the background of the rising cost of electricity. The GCN had a basic policy of using LEDs as the light source from the start of the project. LED modules produced by company P in the Netherlands were adopted in the GCN as a result of discussions with experts and experiments using LEDs provided by various companies. The evaluated factors were (a) better plant growth with far-red light, (b) lower cost, (c) simple construction with a built-in power unit, (d) higher humidity resistance (IP66 rating), and (e) higher color rendering so that plants look green with white light. LED tips of blue, red, white, and far-red are arranged in a 1.2 m module as shown in Fig. 6.1.6. Its energy consumption is 28 W. Three modules are fixed above a 60 cm wide bed and the average PPFD on the cultivation panel is about 180 μmol $\text{m}^{-2}\,\text{s}^{-1}$. Though the addition of the far-red spectrum increases plant growth, it might cause tip-burn and succulent growth of seedlings. It is thought that the effect of adding far-red light in increasing plant growth outweighs the adverse effects, though overall evaluation continues.

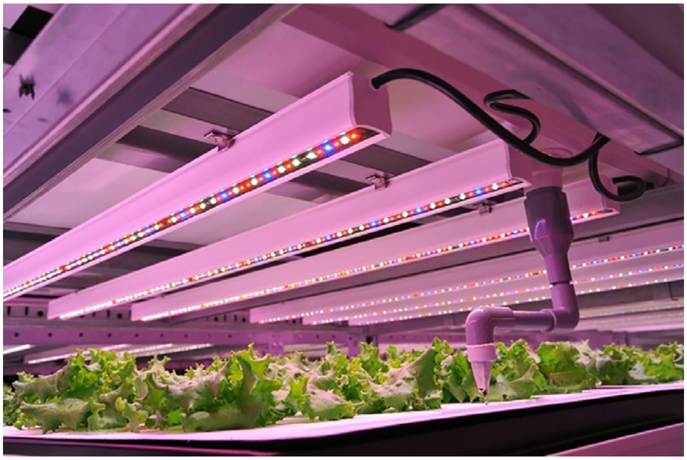


FIG. 6.1.6 LED lighting module.

6.1.2.2 Air Conditioning System

Not only uniformity of temperature, but also a moderate air flow that distributes humidity and CO_2 around leaves is required in a plant factory. One of the problems has been providing moderate air flow to each shelf with low cost and high efficiency, especially in a large-scale plant factory. As a solution to the problem, a vertical duct-blowing system that blows air toward each shelf was established. Though one technique to make the speed of air flow uniform is to increase resistance at the blowout port of a plenum chamber, putting an adequately sized plenum chamber in a limited space is impossible. We tried standardizing the air flow to each shelf by putting slits with different resistances on the blowout ports of vertical ducts. We then established an air-blowing system that blows air from 18 blowout ports of a vertical duct to each of 18 shelves in racks on both sides of the duct. The relationship between the opening ratios of the slits and the air flow of each blowout port was simulated by STREAM general-purpose thermo-fluid analysis software with a structured mesh (Software Cradle Co., Ltd., Osaka, Japan). Some results of the simulation are shown in Fig. 6.1.7. The left panel shows that when every blowout port has the same opening ratio, the air speed from lower ports is higher. The right panel shows that when there are different opening ratios in upper, middle, and lower blowout ports, the air speed from each blowout port is relatively uniform.

The air conditioning load in a plant factory is determined by the sum of the quantity of heat intruding from outside to the factory and the quantity of heat generated by the light sources, and there is little heat load from other devices in the factory. In the GCN, 13,000 LED modules are installed and the heat load reaches 364kW, which is calculated from 28W multiplied by 13,000, even though the heat load is lower for LEDs than fluorescent lamps. The period when the electrical load becomes maximum is the light period. There are many examples of setting the light period to run in the nighttime so that the cost of electrical power is lower due to using the lower midnight rate for electric power use. When the light period is set to nighttime, the heat load from the outside would not have to be considered much, because there is no heat load from solar radiation. The cooling ability of an air conditioner is almost

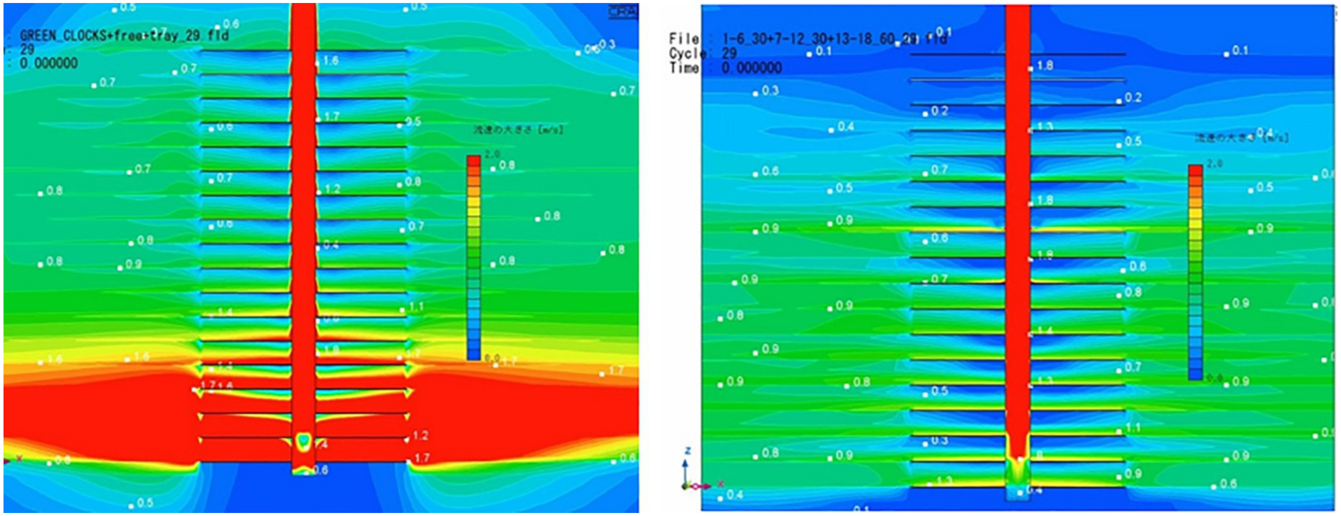


FIG. 6.1.7 A result of computational fluid dynamics.

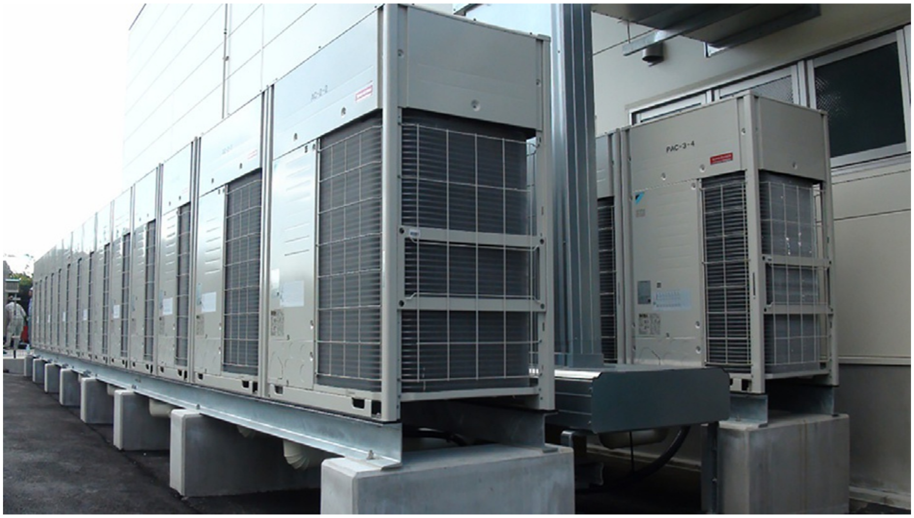


FIG. 6.1.8 Outdoor unit of air conditioner.

enough to compensate for the heat load from light sources in the light period. However, a few percent of the cooling ability for light period is sufficient for the air conditioning load in the dark period because heat load is only intruded heat from outside. Therefore, an air conditioner's capacity can be lower and then electric consumption at peak time can also be lower. The GCN has three air conditioning systems with a 200 kW refrigeration unit to remove the heat load and a 730 m^3 min^{-1} blower to supply air flow to every shelf. The volume of the cultivation room is 5832 m^3 and the ventilation recirculates the air 22 times min^{-1}. The outdoor units of the air conditioner are shown in Fig. 6.1.8.

6.1.2.3 Control System

Because many kinds of systems have to be installed in a plant factory as described above, the system controlling all their instruments is one of the most important components. In the past, self-contained local control systems for individual instruments were common. In the GCN, an integrated control system has been established. Individual control circuits are constructed for each instrument with a programmable logic controller (PLC) in the local system, and in addition, a host PC controls every local system integrally. Logged data for each local system are accumulated in the host PC and can be applied to analysis of their operation and failure. A remote PC can be connected to the host PC through the internet server and every support member can share the data. The system enables the remote diagnosis of plant growth and expedites failure analysis by close linkage between support members. Multiple effects including minimizing downtime are expected. Devices suitable for a producer's own situation should be prepared taking into account advice from experienced people and observation of other plant factories.

6.1.2.4 Peripheral Devices

Since a plant factory is a system producing plants, devices assisting or optimizing its operation are necessary. A wide range of devices such as a seeding machine, transplanting machine, panel washer, packing machine, transporting system, weighing apparatus with metal detection to prevent contamination, air shower, dustproof clothing, masks, and caps, and precooling chamber are needed.

6.1.3 CONCLUDING REMARKS

Though an outline of the fundamental components is provided in this chapter, many other factors such as the structure of the building, its thermal insulation properties, zoning of the operation area, analyzing the flow line of workers, working conditions such as posture and work environment, sanitation control, product distribution, and other factors must be considered in the design of a new plant factory. More than 10 large-scale plant factories that produce more than 5000 lettuce plants per day are now in operation in Japan. As the scale of a plant factory becomes larger, changing the design becomes more difficult. The importance of detailed investigation, computer simulation, and growing plants in a test system is increasing. Furthermore, the development of new technology for both hardware and software is desired since the cost of electricity is rising. We hope that this chapter will help to develop and expand the use of plant factories.

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CHAPTER

6.2

Development of a Seedling Selection Robot Using Green Clock Technology

Shogo Moriyuki, Hirokazu Fukuda

Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, Osaka, Japan

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6.2.1 INTRODUCTION

A plant factory using artificial light offers the potential of stably producing vegetables under constant cultivation year-round, and production can be increased by using vertical multicultivation racks [1]. However, this approach is more costly than production of outdoor-grown vegetables under sunlight, because the initial costs and running costs of the equipment are higher. To reduce these costs, reduction of energy costs, development of more efficient environmental control systems, and more effective cultivation protocols and process are required [1,2]. Moreover, individual plants that grow poorly can cause significant profit losses for plant factories that utilize considerable amounts of electric power for cultivation. Thus, the ability to identify and cull poorly growing (i.e., low-grade) plants at an early stage using so-called seedling diagnosis and selection technology is important for minimizing economic losses in plant factories.

In large-scale plant factories, statistics related to morphological information are quite stable, as shown in Fig. 6.2.1A and B, because the daily population of plants is over 1000.

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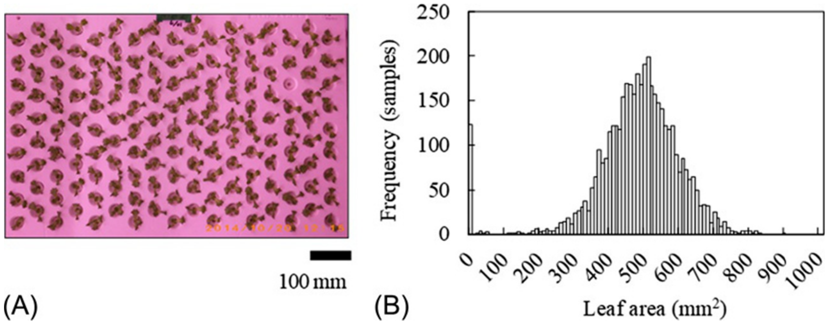

FIG. 6.2.1 Morphological information on lettuce seedlings. (A) Photograph of 153 lettuce plants on a raising panel (13 days after sowing). (B) Histogram of plant size obtained by calculation of projected leaf area for 28 raising panels (4284 seedlings).

Therefore, the accuracy of growth predictors has improved by construction of automatic data acquisition systems and databases to store the biological data. Multiple morphological inspections of leaf size, color, and shape of every seedling provide indices for the assessment of seedling growth in commercial factories. However, physiological information including photosynthetic activity and circadian rhythm (see Section 6.2.3) are also required as indicators for growth prediction.

We introduce the research and development of a seedling selection robot for improving the production efficiency of large-scale plant factories. This robot can diagnose 7200 seedlings a day and produce biological big data (CF images of 10^6 seedlings) in a half year. Moreover, we introduce fundamental research on a seedling selection technique using the circadian rhythm.

6.2.2 SEEDLING SELECTION ROBOT USING GREEN CLOCK TECHNOLOGY IN A LARGE-SCALE PLANT FACTORY

Imaging of chlorophyll fluorescence (CF) is generally used as a highly efficient indicator of factors that affect plant growth, such as photosynthetic capacity and degree of stress [3]. CF results from the emission of red light from chlorophyll a [4,5] when residual light energy is not used for photosynthetic reactions. Accurate measurement of CF, thus, enables the evaluation of photosynthetic photochemical reactions and the status of heat dissipation processes, without the need for physical contact with the plant [6,7]. CF imaging [8,9] has been used to evaluate the heterogeneous distribution of photosynthetic activity over the leaf surface, thus enabling detection of photosynthetic dysfunction caused by biotic or abiotic stress. CF imaging techniques have also been scaled up to enable analyses of whole plants [10], tree canopies [11], and tomatoes cultivated in a large-scale greenhouse [12]. CF monitoring has a practical advantage for simultaneous capture of multiple types of biological information, improving the accuracy of seedling diagnosis. However, there are two tasks needed for construction of a seedling diagnosis system: development of equipment that can measure a time course of CF for a large number of seedlings simultaneously and assessment of the effectiveness of growth prediction based on indices related to the circadian rhythm.

We developed a seedling selection robot using the circadian rhythm in plants (called green clock technology) for *Lactuca sativa* L. seedlings based on CF in a commercial large-scale plant factory that harvests about 5000 lettuce plants every day [13]. Experiments were carried out using seedlings of lettuce (*Lactuca sativa* L. cvs. Frillice and SB555GL, fixed lines of lettuce cultivars from Snow Brand Seed Co., Ltd., Sapporo, Japan). Fig. 6.2.2A and B show a seedling selection robot. The diagnostic apparatus consists of a dark box (900 mm wide, 900 mm deep, and 1200 mm high), a highly sensitive CMOS camera in the upper dark box, and blue LED panels (wavelength 470 nm) in the dark box to excite chlorophyll. In addition, the apparatus includes PC-controlled highly sensitive CMOS camera, an LED controller, a radio frequency identifier (RFID) system, a digital input/output unit, and an automatic program for acquisition/analysis of leaf area, CF, and circadian rhythm data. CF images, such as the one in Fig. 6.2.2C, are obtained by the CMOS camera immediately after the blue LED is turned off. It is possible to measure and analyze chlorophyll fluorescence of 600 lettuce plants simultaneously. Based on the results of measurement and analysis by the seedling selection robot, the transplant robot shown in Fig. 6.2.2D automatically transplants only superior seedlings from the panel used for greening (greening panel) to the panel used for raising the plants (raising panel).

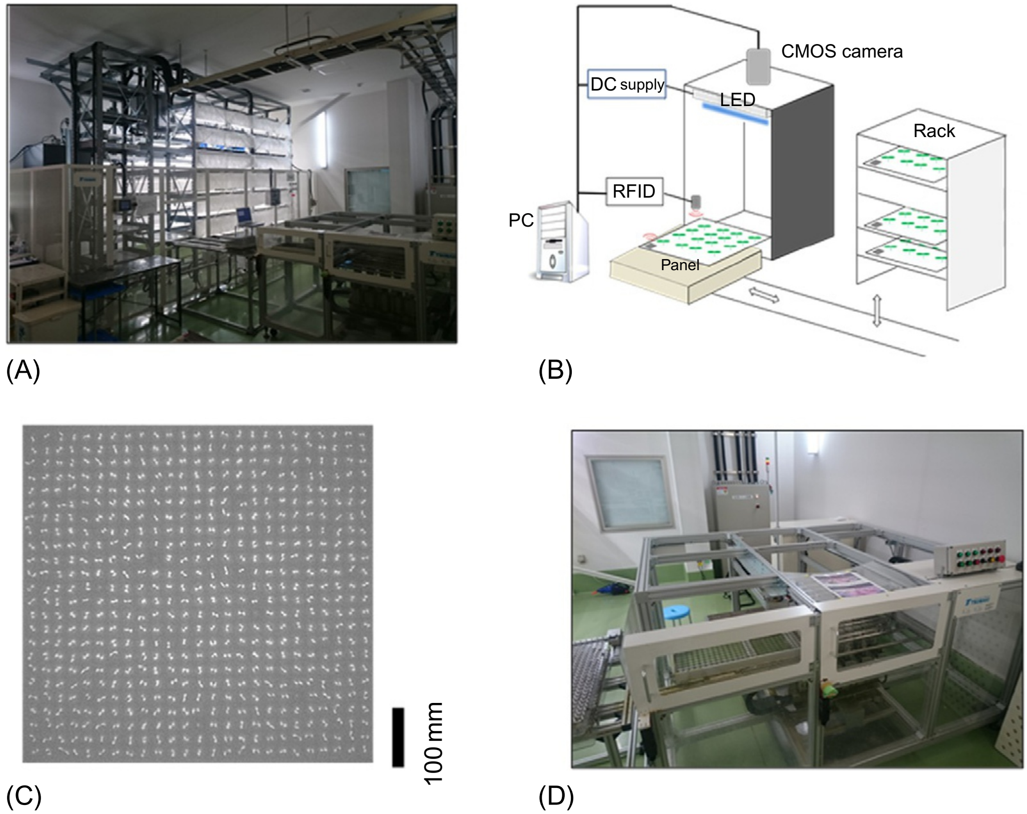

FIG. 6.2.2 A seedling selection robot that uses the circadian rhythm in CF. (A) Photograph of seedling selection robot at Osaka Prefecture University. (B) System chart. (C) CF image of 600 lettuce plants (Frillice). (D) Photograph of robot used to transplant superior seedlings from the greening panel to the raising panel.

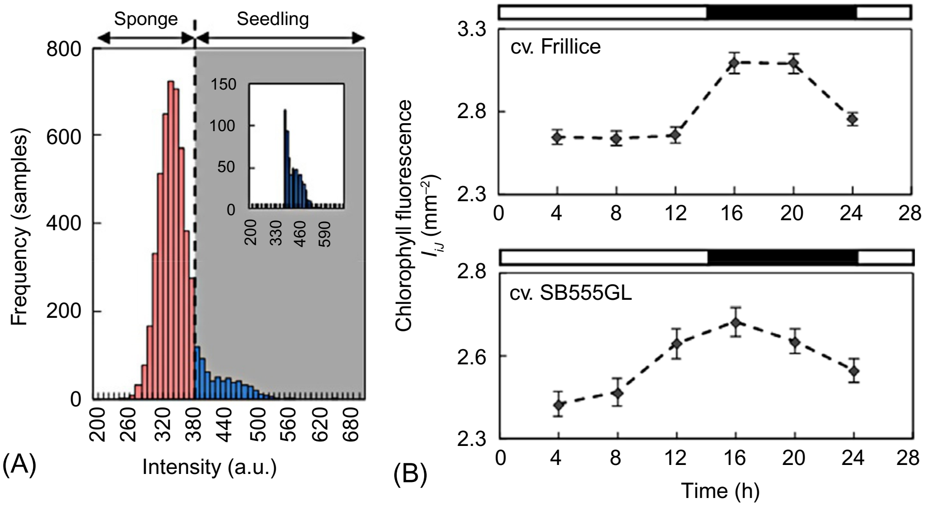

FIG. 6.2.3 Analysis of CF image. (A) Histogram of fluorescent intensity of sponge *(red bars)* and a seedling *(blue bars)*. (B) Circadian rhythm of CF intensity (upper: Frillice, lower: SB555GL). *White* and *black bars*, respectively, indicate light and dark periods in room (15-h light: 9-h dark conditions). Error bars indicate standard error.

This seedling selection robot measured individual size, shape, and CF of each seedling. CF was measured 6 times every 4 h for 1 day on 6 days after sowing. This robot measures the leaf area of each seedling as an index of individual size. To calculate leaf area, the gray-scale CMOS camera captures the distribution of fluorescence intensity between sponge and lettuce simultaneously, as shown in Fig. 6.2.3A. Discriminant analysis is a method to separate the plant distribution from intensity distribution mechanically [14]. Fig. 6.2.3B shows the alteration of I_{ij} during the day from one morning to the next. i means sample number and j means measurement time on 6 days after sowing. All Frillice and SB555GL plants showed circadian rhythms and a peak of CF in the evening. Our seedling selection robot was able to measure CF and circadian rhythms of each plant at an early stage simultaneously. It is also succeeded in extracting the individual size, shape, CF intensity, amplitude of the circadian rhythm, and peak phase of the circadian rhythm.

6.2.3 CIRCADIAN RHYTHM AT THE GERMINATION STAGE

We introduce fundamental research on a seedling selection technique using the circadian rhythm. Fig. 6.2.4 shows the results of highly accurate measurement of circadian rhythm at the germination stage of transgenic lettuce (cv. Greenwave). The circadian rhythm is generated by the endogenous biological clock, namely the circadian clock, and emerges in various physiological processes such as photosynthesis, metabolism, growth rate, and timing of flowering [15–18]. By monitoring the most basic information, i.e., expression of clock genes, we can obtain general information about the status of various clock-regulated physiological processes. The expression of clock gene *CCA1* (*CIRCADIAN CLOCK ASSOCIATED1*) can be monitored using a luciferase bioluminescence assay nondestructively and noninvasively [19,20]. Transgenic *Lactuca sativa* L. (*AtCCA1*::*LUC*), in which a modified firefly luciferase

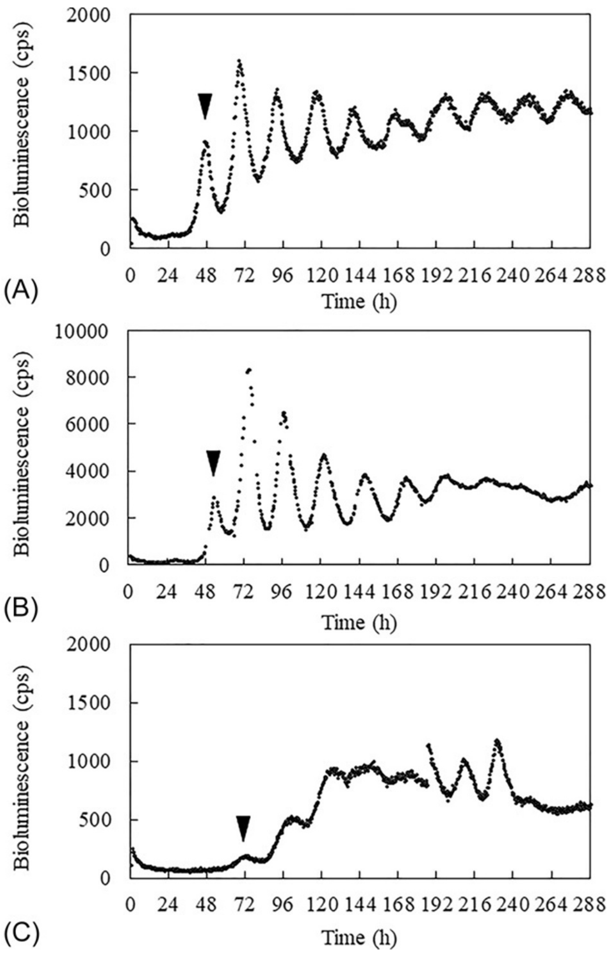

FIG. 6.2.4 Time series of luciferase bioluminescence in lettuce (Greenwave *AtCCA1::LUC*) under continuous light [22]. (A) Time series which maintained amplitude of circadian rhythm until the end. (B) Time series which did not maintain amplitude of circadian rhythm until the end. (C) Time series which did not show circadian rhythm clearly. Black triangles indicate the first peak of circadian rhythm after germination.

gene has been fused to the *CCA1* promoter, was used in our basic study. The luciferase gene is expressed at the same time as *CCA1*, generating the luciferase protein LUC and emitting bioluminescence [21].

The circadian rhythm at the germination stage depends on individuals, as shown in Fig. 6.2.4 Experiments were performed under continuous lighting with red and blue LEDs. In a typical seed (Fig. 6.2.4A), luciferase bioluminescence sharply increased approximately 48h after sowing and showed a high-amplitude circadian rhythm. This timing at 48h corresponds to root emergence (when the root breaks open the seed coat). In other seeds, the circadian rhythm was suppressed after 216h (Fig. 6.2.4B) or was not sufficiently established (Fig. 6.2.4C). Thus, the circadian rhythm depends on the seed. Because the circadian rhythm regulates growth of plants, the growth potential of each seed could be classified by analysis of its circadian rhythm. Although research on the relationship between the circadian rhythm and growth potential at the germination stage has just started, we expect that seedling selection technology will be promoted by advanced knowledge of the plant circadian clock.

6.2.4 CONCLUSIONS

We developed a seedling selection robot for improving the production efficiency of a large-scale plant factory. This robot can diagnose the circadian rhythms at the germination stage in 7200 seedlings a day and produce biological big data (CF images of 10^6 seedlings) in a half year. It is expected that this large amount of biological data will allow high-precision growth prediction. By integrating this seedling biological data as well as data on the cultivation environment and seed data (growing location or country of mother plant, lot number), it may be possible to optimize environmental conditions that maximize the growth potential for each cultivar. Furthermore, using this seedling selection robot, we can explore fundamentals of biological systems, such as internal fluctuations and nonlinearity of plant growth. Plant factories are also expected to be a new research field in plant science.

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CHAPTER

6.3

Cell-Type Modular Plant Factory (V 4)

Yoshikazu Nishida, Nobuaki Okada
**Itoh Denki Co., Ltd. Plant Factory R&D Department, 1146-2 Asatsuma-cho,
Kasai-shi, Hyogo, Japan**

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6.3.1 INTRODUCTION

Automation of vegetable cultivation is not easy; however, there is no doubt that automation is essential to reduce labor costs accounting for one-fourth or occasionally one-third of a manufacturing cost of vegetable production at a closed type plant factory. Not only the labor cost reduction, automation brings remarkable advantages as follows;

1. Unnecessary or harmful substances brought in by humans from outside can be avoided. (Advantage in the safety and sanitation.)
2. Free of such environmental change caused by humans' movements as temperature, humidity, carbon-dioxide, and the wind direction. (Advantage in maintaining the stabilized environment)
3. The safety of workers can be secured. (Advantage in the labor management with no worker accident)

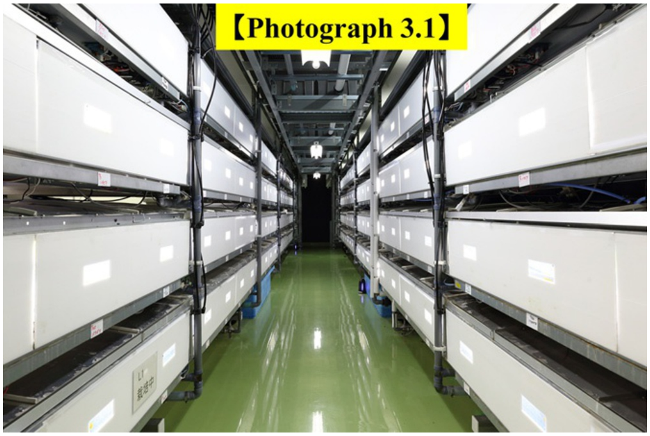
Artificial light type plant factory utilizing underground spaces is realized if the automation of vegetable cultivation is developed by these advantages. Then, "Urban factory," where vegetables can be produced in an area closed to consumption areas, will come true.

On the other hand, the closed type plant factory needs an artificial light for photosynthesis. Artificial light type plant factories in Japan have been consuming the enormous amount of an electric power for the light source and for air condition of their factory to avoid the temperature rise due to the heat generated by the light source. For air condition, not only the control of heat generated by LEDs should be considered, but also the temperature change affected by the surrounding environment. Taking the complicated air condition into account, the temperature of the underground space in an urban farm seldom changes throughout the seasons and 24h, which indicates the optimum environment to reduce the energy required for air condition.

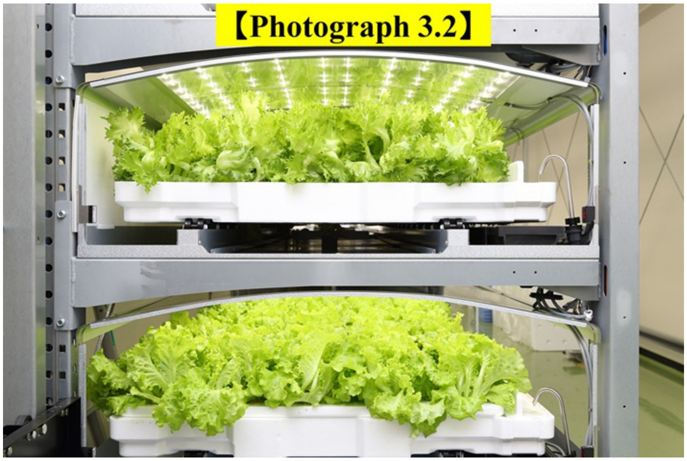
Set aside the artificial light type plant factories utilizing the underground space for the later, this section introduces a newly developed facility which allows energy costs for the light source and air condition to be drastically reduced with no influence of the surrounding environment.

6.3.2 OUTLINE OF THE CELL-TYPE MODULAR PLANT FACTORY

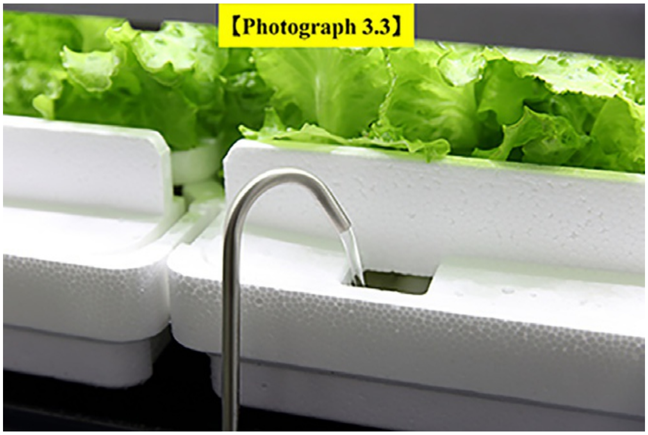
The conventional artificial light type plant factories having high and multi-stage cultivation stages were composed of the open type stages. The cell-type modular that we have developed and practicalized has shrunk the vegetable cultivation space to the minimum, with the structure enclosing the ceiling and both side faces by the wall to the longitudinal direction. We call the factory with the unit structure composed of a series of cultivation facilities with these cell-type modular connected as required and piled up by four-stage two-row form as "The cell-type modular plant factory" (Photograph 6.3.1–6.3.3).



PHOTOGRAPH 6.3.1 Cell-type modular connected by four-stage two-row form. The number of stages can be increased over 10.



PHOTOGRAPH 6.3.2 Cross-section of the cell.



PHOTOGRAPH 6.3.3 Set of the cultivation tray and panel supplying the inside of the cells with the culture solution.

6.3.3 THE STRUCTURE AND FUNCTION OF THE CELL

In the cell shown in Fig. 6.3.1, LED chips that irradiate the light necessary for growing vegetables are mounted on a curved LED light emitting plate and arranged so that uniform light energy is distributed throughout the cultivation panel. In addition, the distance between the LED chips and the vegetables is gradually enlarged according to the height of the seedlings of the vegetables.

The culture solution containing the nutrients necessary for vegetables is supplied from a nutrient solution tank (not shown) to a tray inside the cell by a nutrient solution pump (not shown). And the fertilizer nutrition which the vegetables have absorbed and decreased is detected by the sensor and being fed into the nutrient solution tank from an automatic fertilizer (not shown) and automatic pH control device (not shown). Thus, the nutrient component is always being kept in optimum condition.

Carbon-dioxide required for photosynthesis of vegetables is supplied by the carbon-dioxide cylinder (not shown), and then the bottom fan (not shown) spreads carbon-dioxide evenly through the cell so that the density can be kept between 1000 and 1200 ppm during the light period where LEDs are turned on. On the contrary, carbon-dioxide supply stops during the dark period where LEDs are turned off to reduce the amount of carbon-dioxide consumption to the minimum.

In this way, the cultivation space is minimized by piling up the cells, which produces the optimum space for plant growth, leading to the minimization of the energy for both the LED lights and air condition, and carbon-dioxide consumption amount, as well (Fig. 6.3.1).

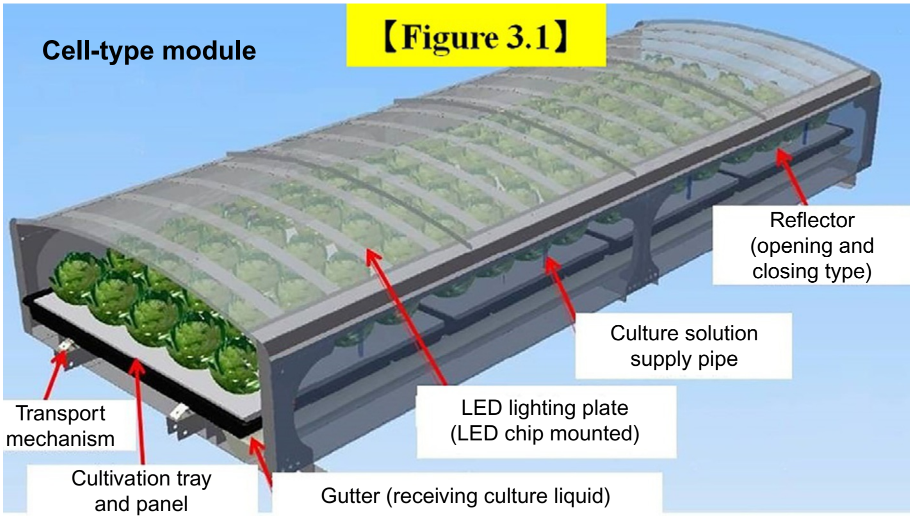

Cell-type module
【Figure 3.1】
Reflector (opening and closing type)
Culture solution supply pipe
LED lighting plate (LED chip mounted)
Transport mechanism
Cultivation tray and panel
Gutter (receiving culture liquid)

FIG. 6.3.1 Cell modular and each part name.

6.3.4 FEATURES

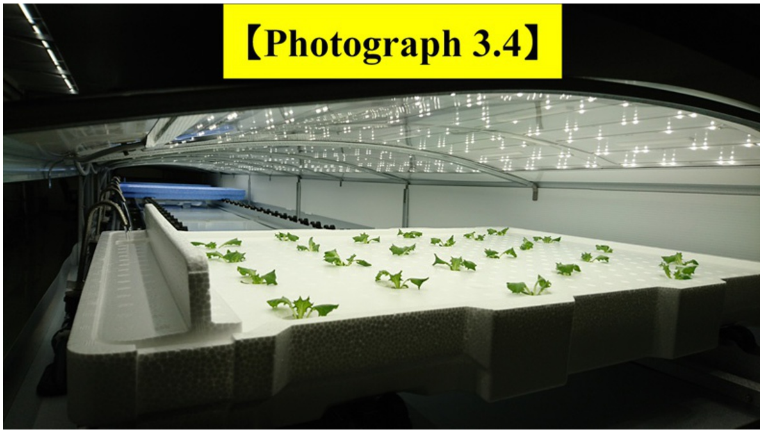
6.3.4.1 The Ecological LED Light-emitting Plate Providing the Entire Cultivation Area With the Even Light Amount

The LED light-emitting plates with LED chips optimally aligned, which realizes the even strength of photon through the entire cultivation area, are expected to make the even growth of vegetables all through the cultivation area possible (Photograph 6.3.4). Moreover, the PFC controller (not shown) can control the light intensity of LEDs according to the growth of seedlings, which significantly saves the energy consumed by the LEDs.

6.3.4.2 Automatic Control of the Culture Solution Circulation

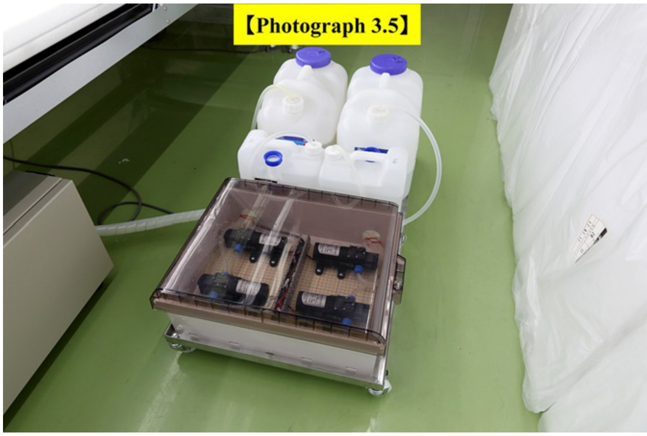
The automatic control system of the IoT automatic additional manure supplement device (Photograph 6.3.5) automatically controls the EC value (the density of the manure in the culture solution) and the pH value. The culture solution in its tank is provided to the cultivation tray inside the cells through the supply nozzles at each stage by the pump. The solution goes around the tray and flows down to the gutter just under the exit on the other side of the nozzle and returns to the tank via its pipe. Our cultivation solution supplement system remains as a little solution inside the tray. Therefore, it is not a complete NFT (Nutrient film technique) system, and it lies in the middle between the NFT and DFT (Deep flow technique) system.

This system produces a thin air layer between the culture solution surface and the cultivation panel; therefore, oxygen can be supplied to vegetable roots, and the slightly remaining culture solution inside the tray allows the roots to absorb nutrients sufficiently. Our designed NFT system is definitely the most suitable for automation because it can reduce the increase of the conveyance weight due to the culture solution, while taking the advantage of DFT (Photograph 6.3.5).



PHOTOGRAPH 6.3.4 LED luminous plate and cultivation panel.

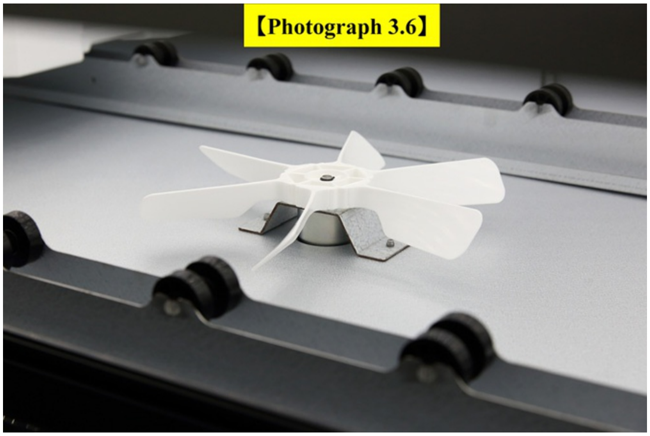
PHOTOGRAPH 6.3.5 The automatic additional manure supplement device (auto-controls the EC and pH).

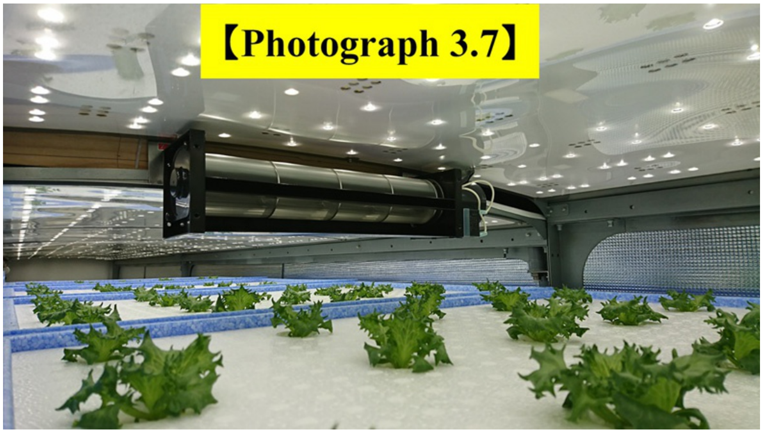


6.3.4.3 The Cultivation Temperature Inside the Cell Closed by the Bulkhead Is Always Kept At the Optimum Value

By the bottom fan right under the tray (Photograph 6.3.6), the air immediately under the tray is fed into the cultivation area. As a result, the temperature of the cultivation area is always controlled by using the heat exchange method which utilized the temperature differences between the culture solution temperature constantly controlled and the room temperature raised by the LED irradiation energy. Moreover, the bottom fan functions to keep the carbon-dioxide density inside the cell evenly to the specified value with its wind, as well. On the other hand, the cross-flow ceiling fan (Photograph 6.3.7) is mounted under the ceiling of the LED light-emitting plate inside the cell functions to promote transpiration of leaves by blowing the suitable wind evenly to the leaves of vegetables inside the cell (Photograph 6.3.6 and 6.3.7, Fig. 6.3.2).

PHOTOGRAPH 6.3.6 The bottom fan.





PHOTOGRAPH 6.3.7 The ceiling fan.

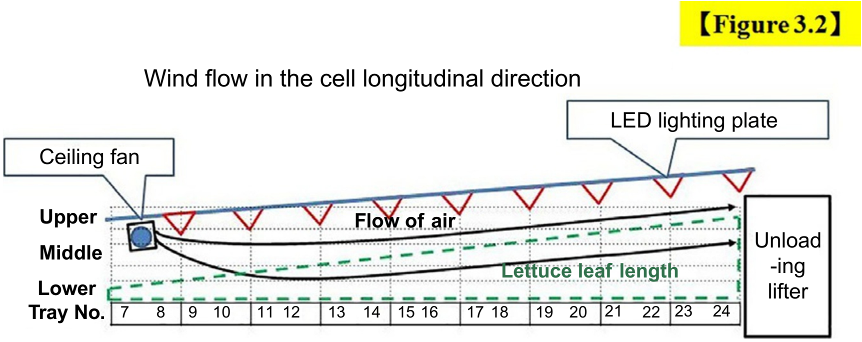
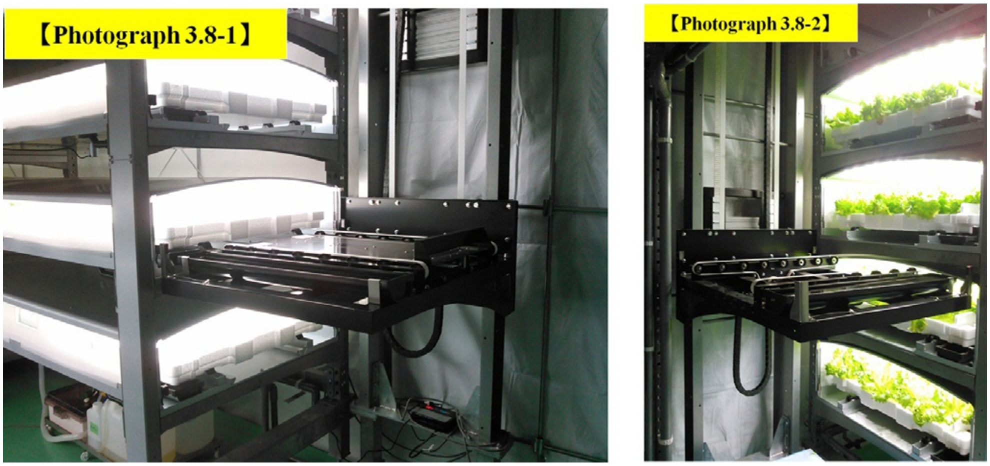


FIG. 6.3.2 Flow of ceiling fan.

6.3.4.4 The Cultivation Tray and Panel Movement System Inside the Cell

The driving unit to move the total 24 cultivation trays and panels at once aligned inside the six-connected cells are mounted on the lifter. When the cultivation tray carrying young seedlings arrives at the lifter, the lifter moves to the specified shelf and stops there, and the mechanism installed on the lifter simultaneously pushes and removes the 24 cultivation trays on the carrier roller throughout the six-connected cells, and finally the head tray of cultivation trays is extruded on the opposite lifter. The cultivating tray which has come out on the opposite side lifter automatically moves to the ground harvesting place as it is carried to the uppermost stage conveyor.

As shown in Photograph 6.3.8, since driving sources such as motors for cultivation tray driving are concentrated existing on lifters, the wirings and control devices and these like concerning them are unnecessary on the connected cells. This has the effect of simplifying the structure of the cell and shelf and drastically reducing the cost of the device (Photograph 6.3.8).

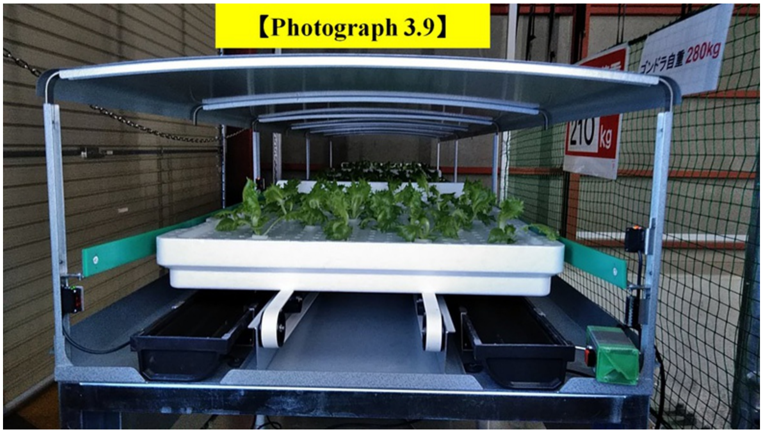


PHOTOGRAPH 6.3.8 The vertical moving lifter (right and left) and the cultivation tray pushout system (left).

6.3.4.5 The Safety Conveying System of the Cultivation Tray

The safety conveying system of the cultivation tray is fully equipped between the ground harvest area and the underground cultivation area. After sowing, germination, planting, and raising seedlings grown around 20 days on the ground level, seedlings are transplanted in the cultivation tray and transferred to the underground gondola lifter (Photograph 6.3.9) and then transferred to the liaison conveyor set at the basement 8 m.

The cultivation tray automatically goes into the four-stage two-rows of cultivation shelves installed at 10 m underground, through a path inclined in around middle of a 27 m long liaison conveyor (Photograph 6.3.10) and right-angle transfer.



PHOTOGRAPH 6.3.9 The gondola lifter carrying underground planting trays planted with seedlings.

PHOTOGRAPH 6.3.10 The liaison conveyor connecting through the cultivation process and the harvest place.

After finishing the 24-day underground cultivation process, the vegetables are entered into the gondola lifter through the contact conveyor again and carried up to the ground. This series of the conveying system has made use of the "id-PAC" technology developed by Itoh Denki Co., Ltd. The "id-PAC" is an epoch-making material handling system which modularizes the conveyor processes by function, aiming at shrinkage of the installation period of time and streamline of the conveyance function (Photograph 6.3.9 and 6.3.10).

6.3.4.6 Production process control system "ICS" From Sowing to Harvesting

ICS is not limited to the control system of vegetable cultivation process, and in case of Makuhari farm, "vechica" also includes raising and lowering between the ground and the underground of seedling cultivation trays and harvested vegetable cultivation panels, and transport control of the underground liaison conveyor; thus, it plays the role of a total control system (Fig. 6.3.3). The above-mentioned id-PAC is incorporated in the ICS to improve the efficiency of transport control running underground.

For example, though the cultivation tray passage detecting sensor is mounted per the cell (four trays each), it is possible to convey the several trays together in a batch. Moreover, it is also possible to transfer a number of trays on the conveyor for a short period of time efficiently, owing to the function to narrow the gap between each cultivation tray to the minimum at any time.

Furthermore, ICS transport control incorporates the IoT technology, on which the world is paying attention right now, and operates under 24-h monitoring regardless of day and night. We can constantly confirm ICS operation status of Makuhari farm near Tokyo(Capital City) at Itoh Denki Co., Ltd. head office in Hyogo prefecture, which is a remote location, through the Internet. If changes occur in the program, remote maintenance that rewrites the program directly from the headquarters can also be executed.

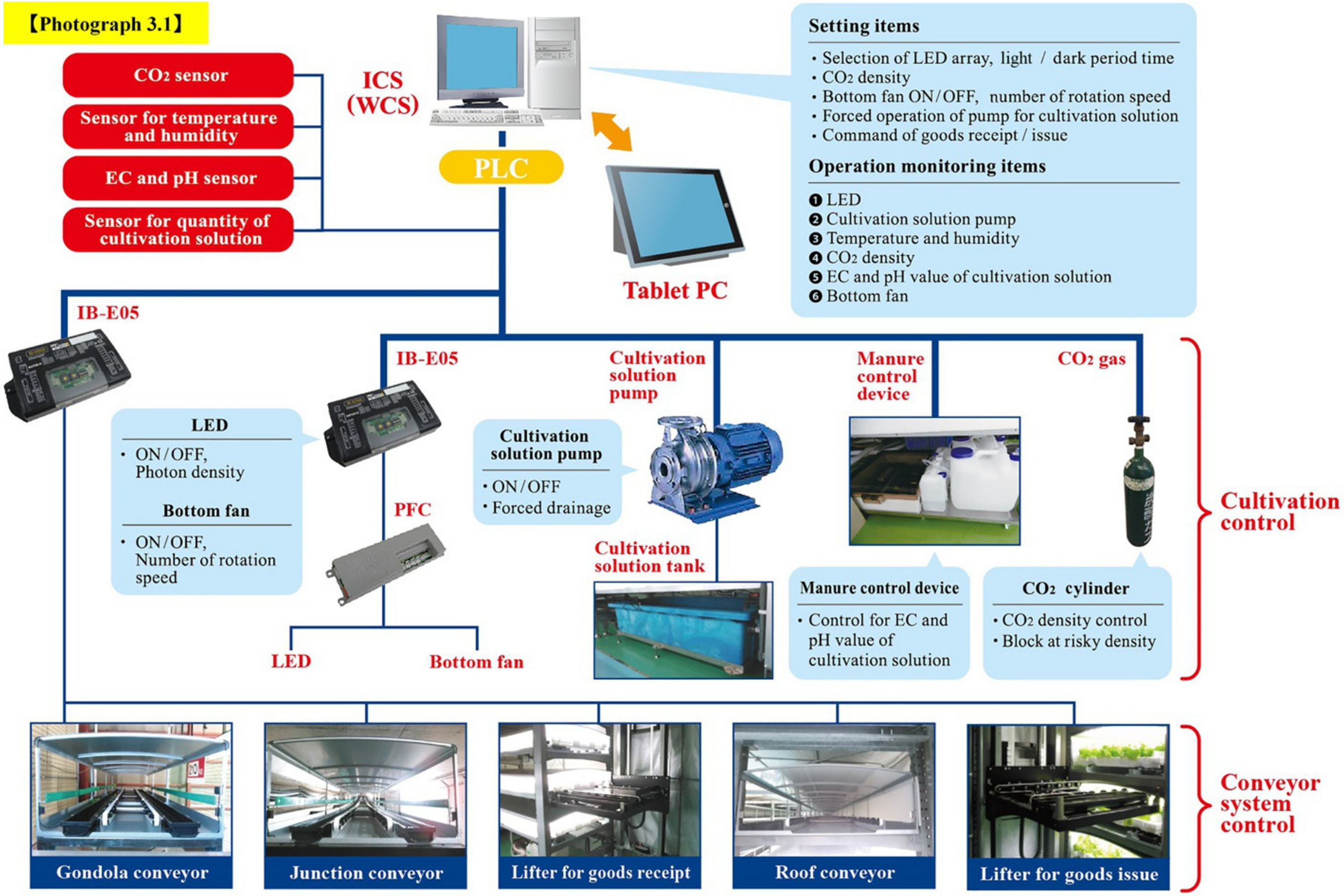

【Photograph 3.1】
CO2 sensor
Sensor for temperature and humidity
EC and pH sensor
Sensor for quantity of cultivation solution
ICS (WCS)
PLC
Tablet PC
Setting items
• Selection of LED array, light / dark period time
• CO2 density
• Bottom fan ON/OFF, number of rotation speed
• Forced operation of pump for cultivation solution
• Command of goods receipt / issue
Operation monitoring items
❶ LED
❷ Cultivation solution pump
❸ Temperature and humidity
❹ CO2 density
❺ EC and pH value of cultivation solution
❻ Bottom fan
IB-E05
IB-E05
LED
• ON/OFF, Photon density
Bottom fan
• ON/OFF, Number of rotation speed
PFC
LED
Bottom fan
Cultivation solution pump
Cultivation solution pump
• ON/OFF
• Forced drainage
Cultivation solution tank
Manure control device
Manure control device
• Control for EC and pH value of cultivation solution
CO2 gas
CO2 cylinder
• CO2 density control
• Block at risky density
Cultivation control
Gondola conveyor
Junction conveyor
Lifter for goods receipt
Roof conveyor
Lifter for goods issue
Conveyor system control

FIG. 6.3.3 ICS, the production process control system.

6.3.4.7 The Makuhari Farm “Vechica” Is An Automated Plant Factory Linking the Ground and Underground

The Makuhari farm “vechica” is a unique plant factory; unique to the world that operates the whole system (Fig. 6.3.4) efficiently by functionally connecting ground breeding and harvesting facilities and underground cultivation facilities.

6.3.5 AN ULTIMATE ARTIFICIAL LIGHT TYPE PLANT FACTORY, THE MAKUHARI FARM “VECHICA”

6.3.5.1 The Makuhari Farm “Vechica” Has Its Growing/Harvest Process Facility on the Ground

For mainly 200 stocks of leaf vegetables as a daily output, there are three divided processes as seeding process to germinate seeds, planting process to increase the number of roots and leaves of germinated species, and after planting greenery seedlings, raising seedlings to young leaves (Fig. 6.3.5). After finishing the growing process, the seedlings are automatically transferred to the underground cultivation process. Meanwhile, at the ground facility, vegetables completing the underground cultivation are sent to the harvest process for root cutting and packaging, and then shipped to the market (Photograph 6.3.11).

6.3.5.2 The Structure of the Underground Cultivation Facility Unit

The underground cultivation facility consists of four stages of cell-type cultivation rack divided into two rows on the right and left. This is defined as one unit, and it is possible to produce 200 stocks every day.

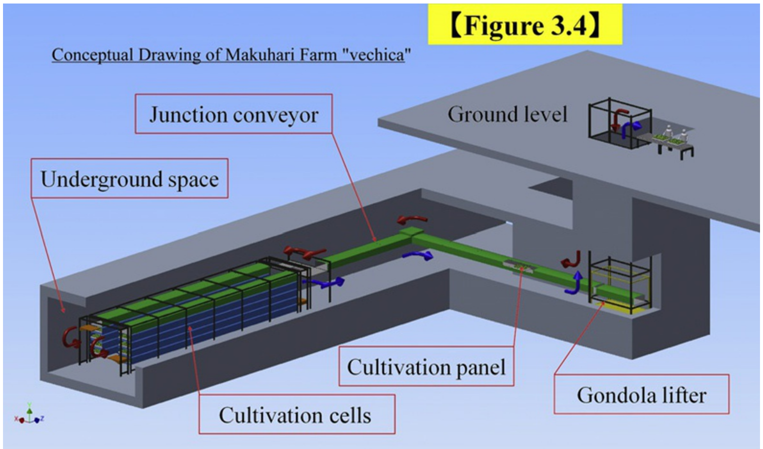
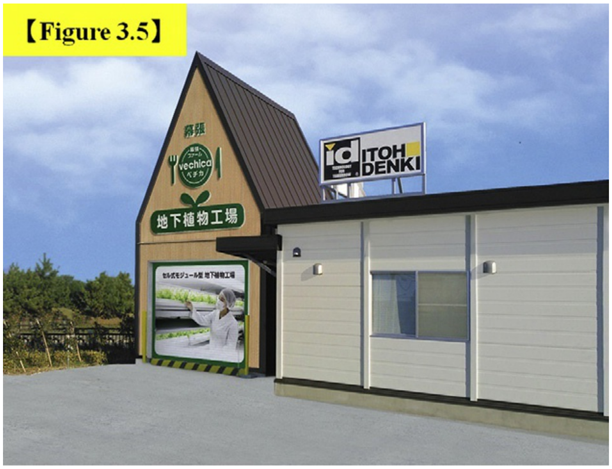
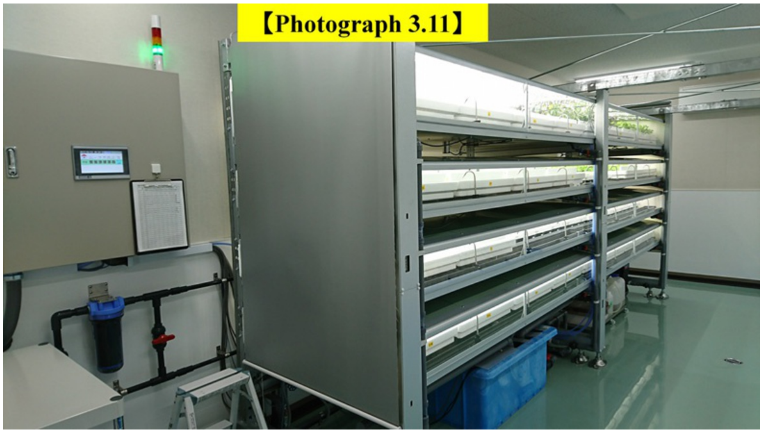


FIG. 6.3.4 Schematic drawing of the Makuhari farm “vechica”.

FIG. 6.3.5 Ground experiment facility of the Makuhari farm "vechica."

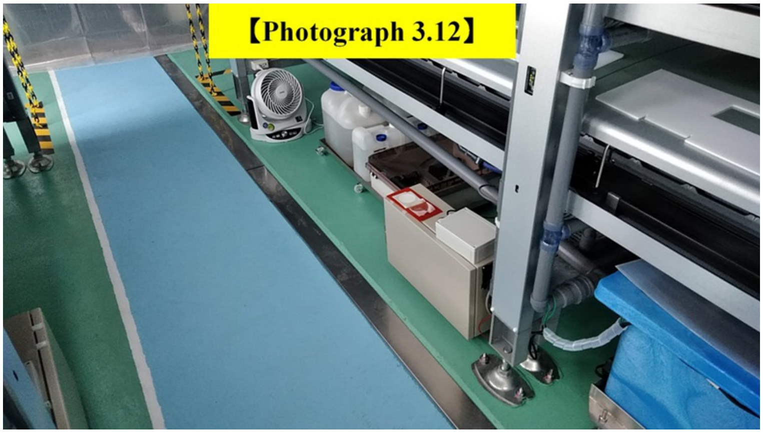




PHOTOGRAPH 6.3.11 The ground verification facility.

Between the two rows of cultivation shelves, maintenance passages are provided, and a space for allowing people to sufficiently enter work during maintenance such as cell replacement is secured. There are the four lifters mounted on both ends of the cultivation rack. Those on the closer end, "OUT side," are for taking out the tray, and those on the other side, "IN side," are for storing the new seedling trays on the stage. Two rows of carrier roller units to move cultivating trays are built in the cell. The uppermost stage of the cultivation rack constitutes a conveyor module for conveying the seedling tray to be received to the receiving side. Directly under the lowest row, the culture solution tank, the culture solution pump, the automatic additional manure supplement device, the control box etc. are housed (Photograph 6.3.12).

In addition, it is possible to unitize as an all-in-one plant factory by collecting four stages and two rows of cultivating racks (Photograph 6.3.13) collectively in house including peripheral devices.



PHOTOGRAPH 6.3.12 The peripheral devices.

PHOTOGRAPH 6.3.13 The Makuhari farm “vechica,” the underground cultivation unit.

6.3.5.3 Flexible Production Scale Expansion

Each cell-type modular unit can produce 200 stocks of leaf vegetables like lettuce per day. At Makuhari farm “vechica,” in the beginning we plan to use one unit as the demonstration and cultivation test. After that, we expect to install 30 units in 2 years, in order to expand capability up to 5000 stocks a day. The connection of the several cell-type modular units easily makes the production scale expansion possible. The connection of the units does not care about the orientation; they can be connected both in horizontal and vertical directions. Besides shelves composed of cells, the uppermost conveying module is also connected at the

FIG. 6.3.6 Cell-type modular cultivation unit.

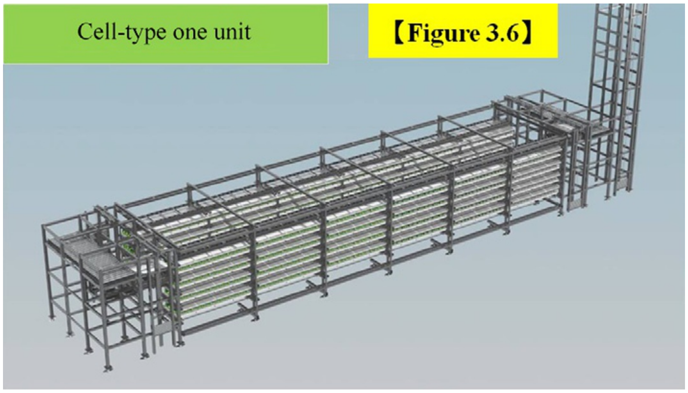
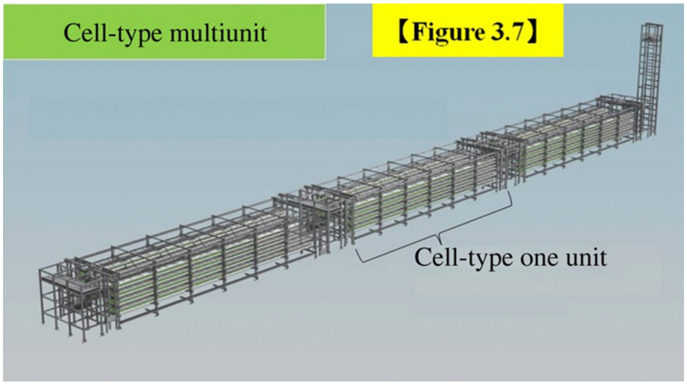


FIG. 6.3.7 Cell-type modular three cultivation unit.



same time; harvesting trays are gathered and lifted by a lifter connecting the ground and the underground.

At the Makuhari farm "vechica," 30 units are expected to be connected in the lengthwise direction stretched tunnel as shown in Figs. 6.3.6 and 6.3.7.

6.3.6 FUTURE PROSPECTS

Fig. 6.3.8 shows an image of the mass production facility of the Makuhari farm "vechica" with its daily production scale increased to 5000 stocks.

The Makuhari farm "vechica" is an ultimate plant factory taking pride in its dramatically high automation rate and profitability, developed by Itoh Denki Co., Ltd.. In other words, the cell-type modular plant factory can be installed flexibly under any location conditions, because it can significantly reduce the personnel expenses by automation and the running energy cost by making full use of the features of the cell. It is the ultimate plant factory equipment that could not be seen in conventional plant facilities.

FIG. 6.3.8 The Makuhari farm mass production factory (the conceptual drawing).

We believe that the operation of facilities under various environments on the surface ground, rather the underground tunnel, is the place to demonstrate the power of a cell-type modular plant factory, and this tunnel environment of underground is a just example of them. This cell-type modular unit has already been installed in an environment wooden house without air conditioning in Yabu-shi, Hyogo Prefecture, which is a governmental special zone for agriculture, and it has been smoothly cultivating lettuce day by day.

Experiencing the cultivations under the various environments throughout Japan, in near future, we will install this system not only in the domestic market, but also in such overseas markets having hot and freezing conditions which are considered not to be suitable for vegetable cultivation, like the desert areas in the Near and Middle East or the frozen Arctic regions, aiming at an expansion of the practical application in the global markets.

CHAPTER

7.1

Universal Design as Welfare Technology

Kuniharu Okuda, Satoshi Okahara, Masataka Kataoka
Graduate School of Comprehensive Rehabilitation, Osaka Prefecture University, Habikino, Osaka, Japan

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7.1.1 INTRODUCTION

Plant factories can contribute to not only industry but also social welfare.

Recently, plant factories are being introduced as new agricultural working facilities for people with disabilities, and as of 2009, about 10% of the plant factories operate under social welfare corporations. Business establishments that employ people with intellectual and mental disabilities are creating workable environments. For example, training employees to understand each other's obstacles through work placement, creating assistance tools, simplifying the work process, introducing a work system based on successful examples, and developing ingenuity.

We believe that a welfare-type plant factory is useful in solving the social problems of the elderly and people with disabilities. Such factories can give them a rewarding job and can promote their health.

7.1.2 PRESENT STATUS OF A WELFARE-TYPE PLANT FACTORY AND EXPECTATIONS FROM IT

7.1.2.1 Utilization of a Plant Factory for Social Welfare

"Sunlight-type" and "fully artificial light-type" plant factories are now in the limelight worldwide. A "fully artificial light-type" plant factory (hereafter, plant factory) grows plants in a closed indoor space, and it has the following advantages:

- It enables rapid production.
- It can provide a stable supply of agricultural crops as cultivation is not influenced by the weather.
- It is suitable as an urban-type agricultural production base because it can effectively utilize unused buildings and spaces under elevated railroads.
- It is possible to cultivate plants with high added value by controlling nutritional ingredients.
- It can grow plants on multiple shelves in narrow spaces.
- It can ensure safety as cultivation is done in a nonpesticide or sterile environment.
- It is capable of providing stable wages and employment opportunities.

Expectations from the plant factory are gradually increasing, such as the safe production of rare plants, the areas at desert or harsh cold zone, or regions with abundant electricity supply.

However, a conventional plant factory has multistage shelves over 2–3 m high that require a ladder to access; thus, a wheelchair user cannot work in such plant factories.

7.1.2.2 What Is a Welfare-Type Plant Factory?

A welfare-type plant factory is "a plant factory in which everyone can work together happily, safely, and forever." Here, "everyone" refers to people ranging from general public to people with disabilities and the elderly.

Our first goal was to create the right environment for a next-generation plant factory where the work, such as flattening and lightening, can be simplified so that it can be done well even in the sitting position (Fig. 7.1.1). This can enable wheelchair users and severely handicapped individuals to work comfortably—people who were previously deemed unfit to work in agriculture as it involves squatting and carrying heavy loads. Automating work at plant factories can greatly reduce physical burden and lumbago.

7.1.2.3 The Organization of a Welfare-Type Plant Factory Division

The welfare-type plant factory division within Osaka Prefecture University was established in 2011. The division members were instructed to integrate ergonomics, health, and engineering knowledge into the development of a plant factory. Our research aims to develop a plant factory work environment that is fully accessible to people with disabilities or the elderly by using ergonomics (human factors) verification, exploring the physiological effects of the work space and environment, and establishing fundamental standards for facility design based on work environment evaluations and on-site inspection models. Furthermore, in order to enable people with severe disabilities to participate in production activities, we are expanding the research subjects to young and elderly people with disabilities, including those with cervical spinal cord injury and cerebral palsy with quadriplegia involving paralysis of the fingers.

This article also reviews research reports on work environments and various assistance tools for people with disabilities and wheelchair users and explains a welfare-type universal design for plant factories.

7.1.3 RESEARCH ON WELFARE-TYPE PLANT FACTORY

7.1.3.1 Work Assessment of Physical Load

In order to construct a comfortable work environment for wheelchair users and elderly people, we first examined and compared the physical exertion involved in carrying out

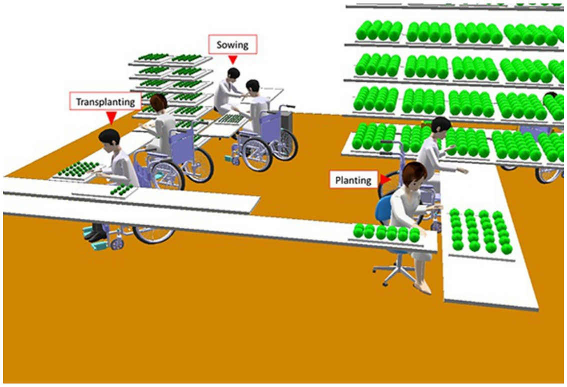


FIG. 7.1.1 A model of a welfare-type plant factory.

the "sowing → transplanting → planting → harvesting" tasks in a standing position versus performing them in a sitting position using healthy workers in the plant factory as subjects. The results indicated that performing these tasks in the sitting position led to decreased muscle contractions in the lumbar region [1] (Fig. 7.1.2).

Next, working time, muscle activity, and subjective fatigue were evaluated for handicapped (spinal cord injury) and elderly people. Each subject was required to sow, transplant, plant, and harvest 20 pieces in a sitting position. It was found that it was possible for people with cervical spinal cord injury to carry out this series of tasks, but their working time was 4–15 times longer than that of healthy subjects, and their muscle activity in the shoulder joint increased (Figs. 7.1.3 and 7.1.4).

If such sitting work is carried out over a long period of time, then it could result in fatigue and muscle pain in the shoulders. In order to reduce the physical burden, we investigated an assistance device for upper limb work involved in such tasks. We examined the amount of activity and fatigue in shoulder joint muscles when using "Graper." "Graper" can be used for upper limb assistance for grape harvesting and other similar tasks. It supports the upper limbs with a shape memory alloy rod of about 60 cm long that has a certain elasticity, useful when reaching hands overhead or forward. It was found that "Graper" reduces fatigue in shoulder joint muscles. Even the subjects with a cervical spinal cord injury who lacked muscular strength in their shoulders were able to work relatively smoothly, especially in the transplantation task.

7.1.3.2 Development of Assistance Tools for Employing People With Severe Disabilities

Businesses that work in specialized fields require constant productivity. We must also respond to changing needs and improving quality. Employees must also respond to the changing needs of the field and the demand for improved quality. Under such circumstances,

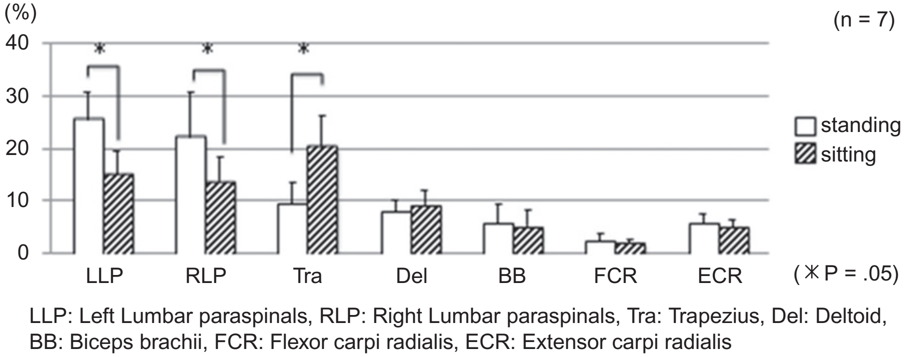
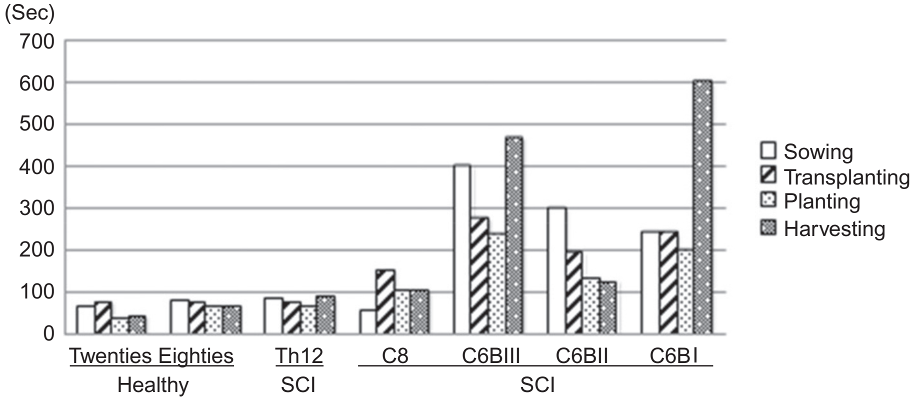
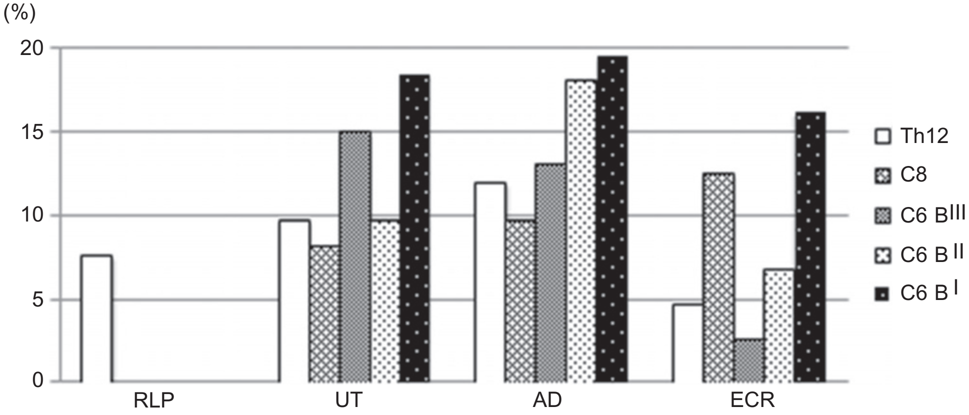


FIG. 7.1.2 Characteristics of the physical burden in the "sowing → transplanting → planting → harvesting" tasks performed in the plant factory were compared in the standing position versus the sitting position. Subjects: healthy people, percent (%): For all muscles, surface electromyography amplitudes were rectified and normalized as a percentage of maximum voluntary contraction. *BB*, biceps brachii; *Del*, deltoid; *ECR*, extensor carpi radialis; *FCR*, flexor carpi radialis; *LLP*, left lumbar paraspinals; *RLP*, right lumbar paraspinals; *Tra*, trapezius.



Th: individual with thoracic spinal cord injury(SCI)
C: individual with cervical spinal cord injury, arranged in order of lighter by Zancolli classification

FIG. 7.1.3 Differences in time required to finish 20 pieces in the sowing, transplanting, planting, and harvesting tasks carried out in the sitting position for healthy individuals, elderly people, and people with spinal cord injuries. *C*, individual with cervical spinal cord injury, arranged in order of lighter by Zancolli classification; *Th*, individual with thoracic spinal cord injury (SCI).



RLP: Right Lumbar paraspinals, UT: Upper Trapezius, AD: Anterior Deltoid, ECR: Extensor carpi radialis

FIG. 7.1.4 Differences in the average muscle activity required to complete 20 pieces in the sowing, transplanting, planting, and harvesting tasks in the sitting position. Subjects: people with spinal cord injury, percent (%): For all muscles, surface electromyography amplitudes were rectified and normalized as a percentage of maximum voluntary contraction. *AD*, anterior deltoid; *ECR*, extensor carpi radialis; *RLP*, right lumbar paraspinals; and *UT*, upper trapezius.

we need to acknowledge the importance of creating simple assistance tools for people with cervical spinal cord injury, as an example.

People with cervical spinal cord injury cannot take the anteversion position due to the paralysis of their trunk muscle group, so the act of reaching forward tends to tire them more than others. As a countermeasure, placing a rotating disk under the tray can help bring in front the part of the tray that has a hole for seeds, thus making the sowing, planting, and harvesting tasks easier for them. For people with cervical spinal cord injuries, tasks such as sowing and replanting seedlings tends to be difficult as it is difficult for them to grasp things due to the paralysis. We are developing various simple assistance tools to make these tasks easier.

- Improved seeding device with a thick hand holder making it easier to grasp even if it is difficult to move fingers
- A special fork that makes it easier to grasp
- Improved seeding machines with thick hands
- Improved trays that have a hole so that seedlings can be easily planted
- In order to simplify harvesting, we created a simplified special catcher that allows individuals to easily harvest plants by sliding the dish. We increased the size of the dishes to ensure the safety aspect of the razor in these specialized aids so that people with severe disabilities can safely use them.

These special assistance tools are developed not only for people with severe disabilities, but also as general-purpose tools that can be easily used by everyone. Their advantage is that they can be introduced easily and are inexpensive.

In order to study the practicality of these tools under the model work environment of the universal design plant factory, we evaluated the working time, muscle activity, and subjective fatigue of the subjects after they carried out 150 rounds of sowing and harvesting using these auxiliary tools and examined the psychological effects on them. It was found that the working time of the subjects with severe disabilities reduced sharply to about 2–3 times longer than the healthy subjects, which was 4–15 times longer than the healthy subjects when they did not use these assistance tools [2] (Fig. 7.1.5). Our hypothesis that such tools can help simplify these tasks for people with disabilities was confirmed. Along with this decrease in working time, the amount of shoulder joint muscle activity and subjective fatigue also reduced. Subjective fatigue, in particular, is reduced by 20%–30% due to the use of assistance tools in sowing and transplantation, and by about 50% in harvesting.

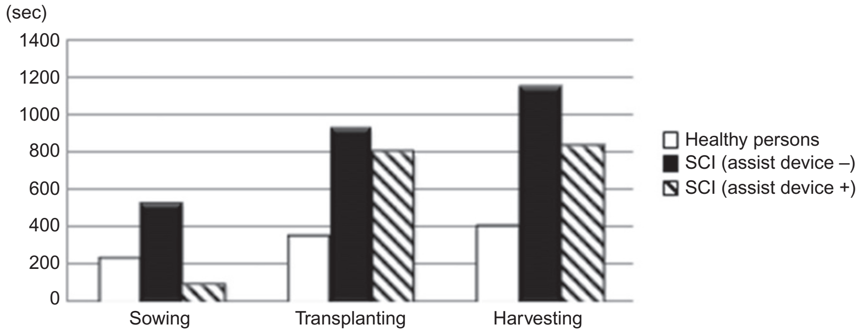


FIG. 7.1.5 The working time for people with severe disabilities when using assistance devices was sharply reduced to about 2–3 times longer than that of the healthy subjects compared with 4–15 times longer than the healthy subjects when not using such devices. SCI: Cervical spinal cord injury ($n = 5$).

In addition, we are working with a joint research company to develop a new cultivation shelf that can be manually moved up and down without the use of an electric lift robot, and if completed, we can greatly reduce its installation cost (Fig. 7.1.6).

7.1.3.3 Healing Effect

This welfare-type plant factory can give people a rewarding job and promote their health. It is also a place that can offer rehabilitation and spiritual healing because it brings people in direct contact with growing green plants every day that provide products that taste delightfully good. Therefore, although it is possible to completely automate plant factories, it is important to take advantage of each individual's capabilities and to consider the benefits of directly touching green plants, while simplifying work and reducing labor. We think that maintaining a balance between manual and automatic is important.

Van Den Berg and colleagues measured the mood of 30 individuals using salivary cortisol and self-report after they performed a stressful problem followed by gardening or indoor reading for 30 min. Their results indicated that gardening elicited neuroendocrine responses, which originated from a decrease in stress and softened emotions [3].

When we compared the scores of the subjects' psychological factors before and after they worked at the plant factory, it was found that the work tended to increase their vigor and reduce their tension and fatigue, for people with a cervical spinal cord injury (Fig 7.1.7). An increase in psychological vigor can be expected in such workplaces that involve working

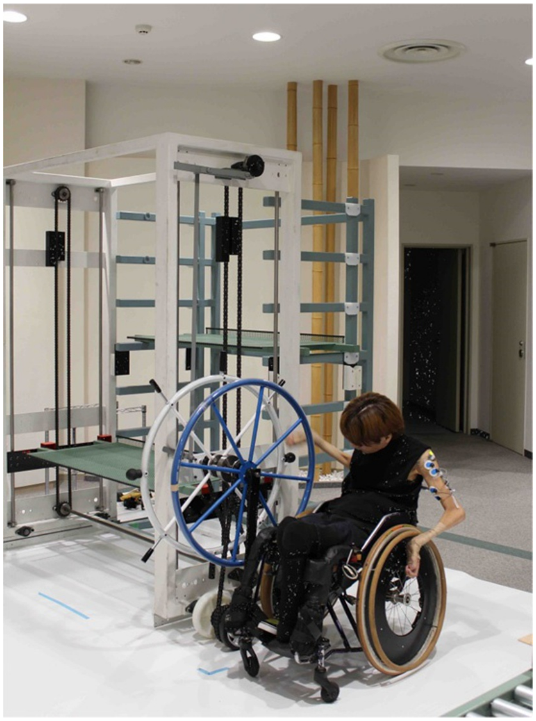


FIG. 7.1.6 Development of a manual multi-shelf (from collaborative research companies).

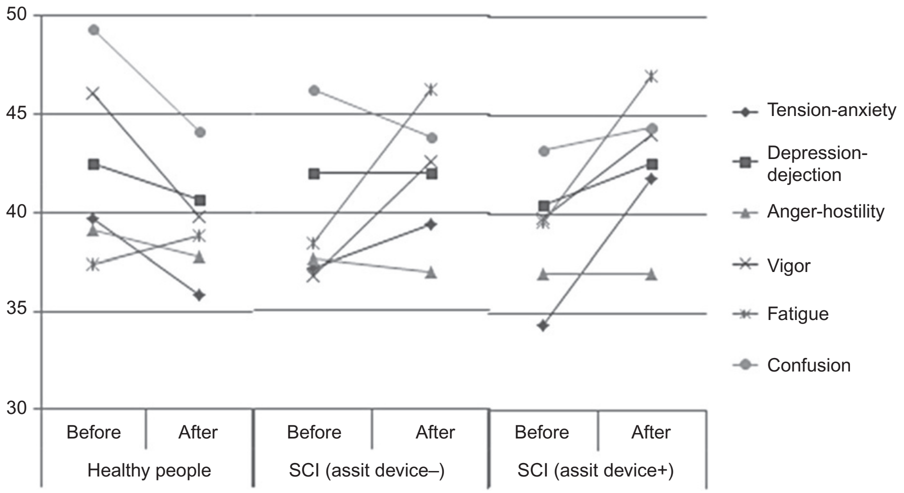


FIG. 7.1.7 People with a cervical spinal cord injury had increased vigor, tension, and fatigue, when psychological changes before and after the work of the plant factory were scored in the questionnaire table of POMS shortened version. SCI: Cervical spinal cord injury.

with plants. On the other hand, it is necessary to pay attention to psychological fatigue caused by delicate plant work.

7.1.3.4 Work Environment Suitable for People With Disabilities and the Elderly

If a worker can install the tray at the window by utilizing the lift robot that automatically transfers the cultivation tray to the multistage shelf, the subsequent cultivation process can be automated, thus making it possible to work well even in the sitting position.

Our analysis of a work environment suitable for people with disabilities and the elderly revealed that, when working, the distance between a growing plant and the wheelchair in which a person is seated should be about 50 cm to enable the person to work comfortably. The previously used tray for planting and harvesting had a depth of 70 × 110 cm, and we made a special tray by reducing it to 50 × 50 cm (Fig. 7.1.8).

In order to perform near the tray, the height of the workbench should allow the armrest of the wheelchair to pass under the workbench. The optimum height is approximately 70 cm. In addition, other environmental improvements introduced in the plant factory reference model are listed below.

- To allow work to be done efficiently, the operation panel of the lift robot should be installed at a height that is easy to access for a wheelchair user.
- The size of the emergency stop button should be adequate and its location should be easily accessible even for people with upper limb difficulties due to paralysis.
- A safety curtain should be installed so that individuals can safely approach the tray installation window of the lift robot.

Based on this information, we created a reference model of a plant factory (welfare-type universal design plant factory) that is suitable for the elderly and people with disabilities in the Universal Design Room at the R&D Center for the Plant Factory (Figs. 7.1.9 and 7.1.10).

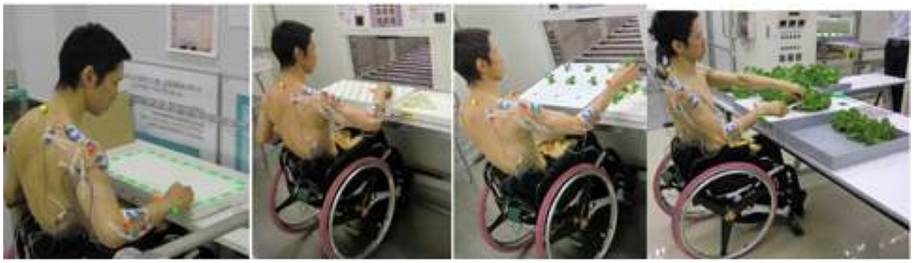


FIG. 7.1.8 An individual with a thoracic spinal cord injury performing the "sowing → transplanting → planting → harvesting" tasks by using a special tray.

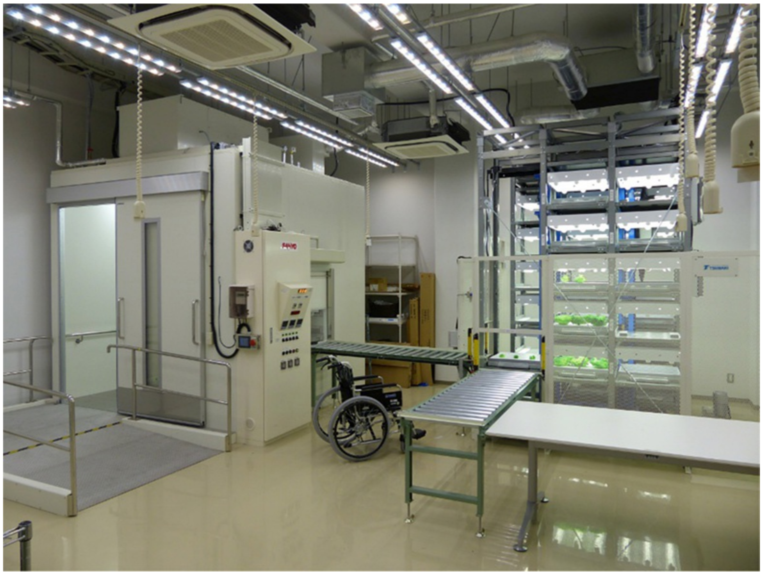


FIG. 7.1.9 We created a welfare-type universal design plant factory model suitable for the elderly and people with disabilities in the Universal Design Room at the R&D Center for the Plant Factory.

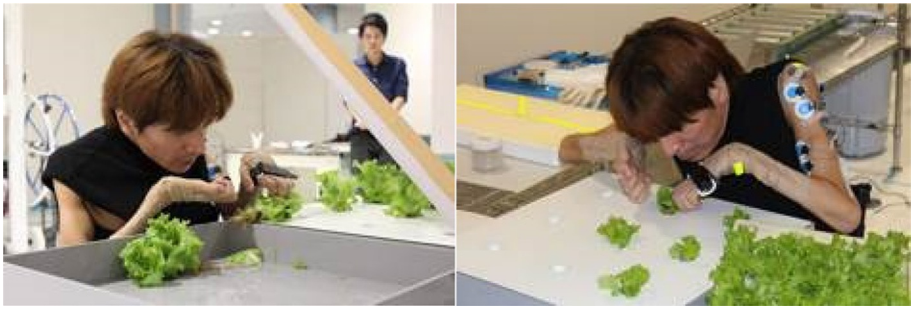


FIG. 7.1.10 An individual with a cervical spinal cord injury in a universal design environment.

7.1.4 KEY ISSUES IN CONVERTING STANDARD PLANT FACTORIES TO WELFARE-TYPE PLANT FACTORIES: BASED ON THE PRESENT SITUATION IN JAPAN

7.1.4.1 Significance and Contribution of Elderly Workers' Agricultural Work

In the 2012 Food, Agriculture, and Rural White Paper, there were 1,060,000 agricultural workers aged 65 and over, accounting for 60% of the total number of workers. The aging population working in agriculture is increasing. Agricultural work is difficult because it involves much physical exertion and lifting heavy loads; thus, agricultural workers are likely to develop musculoskeletal disorder, especially the elderly, making it difficult to continue employment. The welfare-type universal design plant factory is meaningful for the elderly who work there because it is relatively easy to develop a work environment suitable for the elderly at such factories. The following factors are important:

- Be able to maintain and promote health
- To continue to be a contributing member of society
- To increase opportunities to transfer skills cultivated through many years of experience to the next generation

Employing the elderly who wish to continue working also makes them happy and improves their health. The possibility of continuing employment leading to a reduction in medical expenses has been previously reported. Moreover, hindering the work of elderly people with working capability leads to an increase in the burden of intergenerational dependency. The 2006 White Paper on National Life stated that there will be a need to effectively utilize elderly people as a labor force as the labor population decreases with the accompanying declining birthrates. Regarding the ratio of working population to aged population in 2015, people over the age of 65 was supported by 2.3 working individuals in the 15–64 years old age group, but if this working population age group is increased to 15–69 years old, then people over the age of 70 would be supported by 3.6 working individuals. In other words, creating a society where elderly people aged 69 and older can work normally can reduce the burden of social support on younger generations. The benefits of elderly people working positively can be enjoyed by not only elderly people themselves, but also society.

7.1.4.2 Issues Regarding the Employment of Elderly People

Musculoskeletal injury can severely affect production efficiency, and therefore, work environment management to reduce such injuries at work is important. For example, according to the Ministry of Health, Labor, and Welfare's "Survey on occupational disease outbreak situation etc.," musculoskeletal injury consistently accounts for about 60% of occupational diseases from the past to the present. Therefore, it is important to take preventive measures from the perspective of industrial health of workers. An intervertebral disc serves as a cushion in one of the tissues in the waist, and it is between the vertebral body of the lumbar vertebra, which is a hard bone, and the facet joints, and functions to increase the mobility of the lumbar vertebra. Since the way people move and the burden on their body can fluctuate greatly depending on the work environment, the management should make note of the kind of work involved beforehand and take measures to prevent its adverse effects. It is also necessary to consider measures for solving these problems.

7.1.4.3 Countermeasures for the Employment of Elderly People

Our study results showed that when healthy subjects performed "sowing, transplanting, planting, and harvesting" at the plant factory with a standing position and then a sitting position, the sitting posture decreased the burden by 40.2% compared with the standing position on the lumbar muscle group. Focusing only on the lumbar area, the amount of activity of the lumbar muscle group in the sitting position was significantly lower, suggesting its possibility of reducing the burden on the lumbar region.

On the other hand, since it involves raising the hands, shoulder muscle activity in the sitting position was about twice as high as that in the standing position. In the sitting position, the bending angle with respect to the vertical axis passing through the shoulder joint was large, the bending movement of the shoulder joint increased as it needed to support the weight of the upper limb, and the activity amount of the trapezius muscle was high. When developing a work environment that can enable cultivating plants in the sitting position, it is necessary to reduce the burden on the upper limbs.

As described above, it is important to reduce the burden on the musculoskeletal system caused by the poor work posture of elderly workers, and from the perspective of plant factory design, it is important to reduce physical labor and improve the work environment.

7.1.4.4 Significance of Workers With Disabilities in Agriculture

According to the Cabinet Office's Fiscal Year 2015 White Paper on Persons with Disabilities, the average monthly income of regular employees with physical, intellectual, and mental disabilities was 254,000, 118,000, and 129,000 yen, respectively. On the other hand, the wages assigned for employment continuation support type A (66,000 yen) and for hire continuation support type B (14,000 yen) are very low. Individuals without work accounted for about 60%. It is very difficult to live independently without an allowance, pension, or assistance.

The Ministry of Health, Labor, and Welfare's Employment Survey in 2013 reported that the employment rate in the agriculture, forestry, and fishery fields is remarkably low: 0.6% for people with intellectual disabilities, 0.5% for people with mental disabilities, and 0.1% for people with physical disabilities.

Efforts to utilize agriculture for the employment of people with intellectual disabilities, especially considering the benefits obtained from touching plants, are also being undertaken, and its effects have also been reported.

Regarding our study, some of the comments made by the subjects with physical disabilities are as follows: "It seems that we can work in the plant factory," "It's fun," "Even though we our regular jobs provides a monthly income of only about 10,000 yen, we can expect more income from the plant factory," "Growing safe and delicious crops, I want to work in such places." There were many subjects who hoped for the practical application of our reference model.

However, irrespective of the desire of wheelchair users and people with physical disabilities, it is impossible for them to do traditional agricultural work as it requires able-bodied individuals with high cardiopulmonary function. The welfare-type plant factory's social significance is remarkable, such as the expansion of occupational areas for people with disabilities in agriculture and their participation in production activities.

7.1.4.5 Issues Regarding the Employment of People With Disabilities

In 2009, the Ministry of Health, Labor, and Welfare estimated that 826,000 of the 2 million people with disabilities between the age of 15 and 64 years were employed. Of these, only 335,000 people (16%) are regularly employed. Approximately 55.3% of companies did not achieve the statutory employment rate of people with disabilities, and 47,888 companies did not fully promote the employment of people with disabilities in 2014.

Companies that have not employed people with disabilities until now cannot overlook employment of people with disabilities, but they still shun such people. These companies report that they do not know whether there is a suitable job inside the company for people with disabilities, do not know how to improve their work environment so that the workplace is safe, and are not sure if they can fully grasp those abilities at the time of recruitment. In addition, while people with relatively high levels of production capacity who do not have severe disabilities are more likely to be employed, it is difficult for people with severe disabilities to work. There is concern that the polarization of workers and nonworking people will increase.

7.1.4.6 Contribution to the Economy and Jobs in the Social Welfare-Related Field

We hope that our research leads to the commercial development of a welfare-type universal design plant factory where people with severe disabilities can work happily. A small- to medium-sized welfare-type universal design plant factory can produce 150 pieces per day, in addition to the sales of plants and subsidies for promoting the employment of people with disabilities that award employers 2.4 million yen over 3 years. The productivity of people with severe disabilities is about one third of that of healthy individuals, so their estimated monthly wage would be about 100,000 yen. The following can be expected:

- Involvement of social welfare corporations in the social cycle through production activities
- Contribution to an increase in the wages of elderly people and welfare workers.

A welfare-type universal design plant factory is capable of effectively utilizing narrow land, including land under elevated railroads or abandoned buildings in urban areas with improved transportation, as a workplace. People with disabilities and the elderly who live in the area can enjoy working every day in a more familiar place, in addition to taking advantage of the benefits of local production of delicious and high value plants that are fresh, safe, and secure and can generate significant profits. With the declining birthrate and an aging population, support for the employment of people with disabilities and the elderly is greatly needed, as are various disability employment policies.

7.1.5 CONCLUSION

Our research revealed that the urban welfare-type universal design plant factory that provides excellent accessibility and air conditioning facilities can possibly be an ideal future workplace where the elderly and people with disabilities can work safely using special assistance tools. A rich society is one in which all people are guaranteed to have peace of mind, a purpose for living, a secure wage, and a comfortable living space and environment. The welfare-type universal design plant factory can let needy people continue to work forever. It can be applied as an employment model for the normalization of society.

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CHAPTER

7.2

Optimizing Plant Factory Performance for Local Requirements

R.J.P. Janssen[*], *M.P.C.M. Krijn*[†], *T. van den Bergh*[*], *R.F.M. van Elmpt*[*], *Celine C.S. Nicole*[†], *Udo van Slooten*[*]

[*] **Horticulture LED Solutions, Signify, High Tech Campus 7, Eindhoven, The Netherlands**
[†] **Lighting Research, Signify, High Tech Campus 7, Eindhoven, The Netherlands**

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7.2.1 INTRODUCTION

Plant Factories (also known as indoor farms or vertical farms) are gaining widespread attention over the last few years. Pioneered in Japan, the last few years show an acceleration in the adoption of plant factories in other regions such as the United States, Canada, Europe, and South-East Asia. The differences between regions are becoming apparent: whereas the United States and Canada focus mainly on the local perspective, in Europe the focus is on optimizing yield and quality, while in Japan it is on food safety and maturing the production technology.

Plant Factory using Artificial Light
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In this overview, we will outline the main reasons for these differences and the opportunities for plant factories to further optimize their operations by focusing on the most critical factors to grow efficiently.

Recent advancements in technology, knowledge of plant growth, and market development have resulted in plant factories becoming economically viable as a facility for the year-round production of high-quality leafy vegetables and herbs. Especially LED lighting has proven to be an enabler in this respect.

In plant factories, the plants are grown in multiple layers, in a fully controlled and closed environment, without daylight, and close to the consumer. Mostly, LED lighting is used for growing light as well as steering light. With LED lighting, the light level, spectrum, and photoperiod can be tuned to result in optimum growth in terms of yield and quality [1,2]. LEDs have shown to be suitable for multilayer growth because of their form-factor, cool temperature, and high energy efficiency. As a result, they can be located close to the plants [3].

The economic viability of plant factories is influenced by a number of factors. Compared to greenhouses, plant factories require large investments. Also, the cost of operation of a plant factory is relatively high [4]. However, plant factories are very efficient production facilities: the yearly production per unit of growth area easily exceeds the production in the most advanced greenhouses. To further improve the viability of plant factories and to be able to monitor the effectiveness of advances in systems and knowledge relevant for growth, it helps to define key performance indicators (KPIs).

In this overview, we present a minimum set of KPIs relevant for the economic viability of plant factories. This set is sufficiently complete to be able to evaluate the economic viability of a plant factory.

An important KPI for the efficiency of growth is the one relating biomass production to the integral amount of light used for the production (this KPI is hereafter called light-use-efficiency or LUE, expressed in $\mathrm{g\,mol^{-1}}$). We show how this KPI can be maximized by an optimal lighting design in combination with a transplanting strategy that maximizes the interception of light by the plants. We present a model to estimate the theoretical maximum LUE achievable. We illustrate our approach with specific examples of what we achieved for lettuce growth and the growth of several types of herbs.

Since the use of energy in a plant factory represents a considerable fraction of the cost of operation, we also discuss in some detail a KPI related to the energy efficiency of LED lighting (performance indicators for the efficiency of other resources are out of scope [5]). Next to a high growth efficiency, resulting in a high production, also crop quality is important. It is not obvious that a high quality can be achieved without compromising a high production. As an example, we show that the coloration of lettuce and the reduction of nitrate in lettuce can be achieved by a preharvest lighting strategy such as not to compromise the overall growth efficiency.

7.2.2 BACKGROUND INFORMATION

Even though the performance indicators mentioned in this chapter are valid for all indoor farms, it is important to understand some of the dynamics in the different markets.

Indoor farming startups have attracted significant investments over the past few years. According to data provided by AgFunder[1], indoor farming startups have raised $285 million since the start of 2017, with especially US-based vertical farms like Aerofarms, Plenty, and Bowery pushing the sector to its highest ever investment levels. These farms focus mostly on the local perspective and compare their products with leafy greens and herbs grown in Salinas valley in California. Their main differentiators are the limited food miles, savings on water usage, and pesticide-, herbicide- and fungicide-free production. With quite a lot of capital available, most of these startups create their own systems, to have proprietary solutions for potential future roll-outs. These systems require significant investments with typically less automation, lower yield, and lower quality compared to the systems deployed in Europe.

Regarding Europe, one notices that large indoor farming operations are mostly focused on monoculture crops with a clear drive for cost and quality. Europe, and especially the Netherlands, is one of the driving forces of high-tech horticulture innovations. Last year, the Netherlands was the second biggest exporter of vegetables in the world. Furthermore, the Dutch agri-food industry accounts for about 20% of the Netherlands' total export value and has the second highest private R&D investment rate in Europe (Sources: Government of the Netherlands, Holland Trade[2]). Given the small footprint of the country, it is mainly high-tech greenhouses that drive this production. Technology used in these Greenhouses, such as automation, climate control, lighting, and automated irrigation, are also available for indoor farms. Already in 2012, company Deliscious in Beesel built a fully automated indoor farm growing young lettuce plants under LED lighting. Doing this, they solved the issue of having difficulties guaranteeing a constant supply of high-quality young plant material year around. In 2019, Staay Food Group will open a vertical farm in Dronten, directly linking the production of lettuce to the processing steps required for packaged salads. By combining growing and processing in the same location, they reduce food miles, waste, logistics challenges, and the risk of contamination.

Asia and especially Japan have been leading in technology development for plant factories since the beginning of the century. With an emphasis on cleanliness and uniformity, the developments have mainly been on the technical aspects of the farm. The production yield of plant factories in Asia is typically measured in the number of heads or plants produced per day, rather than kilograms. Therefore, it remains rather difficult to assess and compare the productivity of the plant factories with others.

Below, we will list the main KPIs that can determine the success of a plant factory. As stated before, this list is valid for all indoor farms. Regional differences may lead to a different layout and product specification, but the drivers for success will remain the same.

[1] https://agfunder.com/

[2] Source https://www.hollandtradeandinvest.com, see online publications of the Ministry of Foreign Affairs, Editor Erika Koehler, Holland Compared, second ed., 2017

7.2.3 MATERIALS AND METHODS

The experiments reported in this overview were carried out at the Philips GrowWise research center in Eindhoven, The Netherlands. This facility includes eight climate cells with independent regulation of lighting, climate, and irrigation. The lighting systems used are based on Philips Greenpower LED production modules. The lighting is calibrated in a defined rigorous procedure using a JETI spectrophotometer (Specbos 1201, JETI Tech. Instr. GmbH.).

We used a hybrid “shallow water” cropping system that avoids some weaknesses inherent to ebb and flow, nutrient film technique (NFT), and aeroponic systems (nozzles sensitive to clogging combined with a limited water buffer). The shallow water system features a shallow layer of water (water depth is maintained by an overflow drain) and a hard-plastic panel with holes in which plant holders are positioned (net pots) with a coco coir substrate (Jiffy products international BV, Zwijndrecht, The Netherlands).

Lettuce seeds were obtained for Salanova and butterhead lettuce types (Rijk Zwaan B.V., de Lier, The Netherlands) and herbs (Enza Zaden, Enkhuizen, The Netherlands). We used a standard nutrient solution for lettuce and herbs. We tested the effects of transplanting strategies on the light use efficiency (e.g., $750 \rightarrow 33$ vs $750 \rightarrow 100 \rightarrow 33$ plants m^{-2}). Experiments were performed for a range of temperatures (22–30°C) and CO_2 concentrations (400–1600 ppm). Relative humidity was maintained at 75%–85% with a photoperiod of 14–18 h per day and a light intensity in the range of 180–400 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$.

7.2.4 KEY PERFORMANCE INDICATORS

Table 7.2.1 lists the main key performance indicators (KPIs) relevant for determining the economic viability of plant factories. The table lists the KPIs relevant for calculating business case metrics such as payback period and net-present-value. Also, listed are KPIs relevant for estimating production yield and energy use. In order to be able to compare numbers from different plant factory projects, we suggest expressing the numbers as much as possible per unit of growth area.

From an expenditure perspective, the investment to realize a plant factory as well as the cost of operation are of importance. The cost of operation can be split into a direct part and an indirect part. The direct part scales are proportional to the production and includes the cost of labor, energy, and consumables (like seeds, substrates, water, CO_2, fertilizers, packaging materials, transport, etc.). The indirect part includes other costs (like marketing, insurance, maintenance, overhead, etc.). The yearly income can be estimated from the sales price of the produce in combination with the net yearly production.

KPIs related to the efficiency of growth and the gross production are also listed in Table 7.2.1. As an estimate of the growth efficiency, we consider the above-mentioned light-use-efficiency (LUE). The definition of the LUE and typical values to expect will be discussed later on in more detail. The gross production is defined here as the weight of the sellable produce harvested per square meter of growth area per year, assuming the up-time of the plant factory as well as the degree of utilization of the available growth area

TABLE 7.2.1 Key Performance Indicators

KPI	Units
Investment	\$ m^{-2}
Cost of operation	\$ m^{-2} $year^{-1}$
Direct cost of operation	\$ kg^{-1}
Indirect cost of operation	\$ m^{-2} $year^{-1}$
Sales price of produce	\$ kg^{-1}
LED module efficacy	$\mu mol\,J^{-1}$
Energy efficiency of production	$kg\,kWh^{-1}$
Light-use-efficiency (LUE)	$g\,mol^{-1}$
Light utilization	%
Gross production	$kg\,m^{-2}\,year^{-1}$
Plant factory up-time	%
Growth area utilization	%

to be 100% (i.e., ideal circumstances). The gross production, P_{gross}, can in principle be obtained by combining the LUE with the daily radiation integral (DRI, including any far-red light) offered to the plants[3]:

$$P_{\text{gross}} = \text{LUE} \times \text{DRI} \times \frac{365}{1000} \tag{7.2.1}$$

where P_{gross} is in $kg\,m^{-2}\,year^{-1}$, LUE is in $g\,mol^{-1}$, and DRI is in $mol\,m^{-2}\,day^{-1}$. By multiplying the gross production with the actual plant factory up-time and degree of utilization, the net production is obtained. In practice, the up-time will deviate from 100% as a result of the following (nomenclature as used by the semiconductor industry):

- *Nonscheduled time*: time during which there is no demand.
- *Unscheduled downtime*: time that intervention is required, and production is halted.
- *Scheduled downtime*: time required for maintenance and cleaning.
- *Engineering time*: time needed to correct and tweak the system.
- *Stand-by time*: system is ready for production but waiting for another step.

Also, the available growth area will not be fully utilized in practice (e.g., due to limited demand, changes in the crop mix, or limitations of the logistics system).

---

[3] Implicitly assuming that the DRI is the same for each day from seeding to harvest.

7.2.4.1 Energy Efficiency of LED Lighting

The energy efficiency of LED lighting modules has improved substantially over the years. For LEDs, the wall plug efficiency, η_{wp}, can be expressed as the product of a number of efficiency factors limiting the overall efficiency:

$$\eta_{\mathrm{wp}} = \eta_{\mathrm{driver}} \times \eta_{\mathrm{opt}} \times \eta_{\mathrm{extr}} \times \eta_{\mathrm{int}} \times \eta_{\mathrm{inj}} \tag{7.2.2}$$

Here, η_{inj} refers to the injection losses of electrons and holes into the active semiconductor materials: these losses result in Ohmic heating inside the semiconductor materials as well as the semiconductor-electrode interfaces. η_{int} is the internal quantum efficiency and equals the fraction of the injected electrons and holes that is able to recombine by emitting light. The light emitted has the tendency to bounce around inside the semiconductor materials, due to the high index of refraction of these materials and get absorbed: η_{extr} refers to the fraction of the light that is able to escape. The light that is emitted by the LED has to pass primary and, possibly, secondary optics, resulting in some optical losses $(1-\eta_{\mathrm{opt}})$. Finally, also the driver to supply the LEDs with a constant current suffers from losses: the driver efficiency is denoted by η_{driver}. Typically, at the moment, each of these efficiency factors is at a level of around 85%–90%, resulting in an overall wall plug efficiency of typically 40%–50%. This holds for LEDs emitting in the blue, red, and far-red part of the spectrum and depends, among others, on peak emission wavelength and the current through the LEDs. LEDs emitting in the green part of the spectrum in general have considerably lower efficiencies.

A convenient KPI for the efficacy of LED lighting is the amount of light emitted by the lighting system per unit of energy consumed, expressed in $\mu\mathrm{mol\,J}^{-1}$ (or $\mathrm{mol\,kWh}^{-1}$). This lighting efficacy relates to the wall plug efficiency as follows:

$$K_{\mathrm{wp}} = \eta_{\mathrm{wp}} \times K_{\mathrm{max}}, \tag{7.2.3}$$

where K_{max} is the maximum lighting efficacy theoretically possible (in $\mu\mathrm{mol\,J}^{-1}$; making use of the fact that LEDs are narrow-band emitters):

$$K_{\mathrm{max}} = \frac{10^6}{N_{\mathrm{A}}\ h\ c}\lambda_{\mathrm{peak}} \cong 8.36 \times 10^6\ \lambda_{\mathrm{peak}} \tag{7.2.4}$$

Here, N_{A}, h, c, and λ_{peak} are Avogadro's number, Planck's constant, the speed of light, and the peak emission wavelength of the LED (expressed in meters), respectively.

The dominant LED emission wavelengths used for plant growth in plant factories are 450 nm (blue), 660 nm (deep-red), and 730 nm (far-red). At these wavelengths, K_{max} is 3.8, 5.5, and 6.1 $\mu\mathrm{mol\,J}^{-1}$, respectively. Note that the above does not hold for phosphor converted LEDs: Phosphors can be used to convert blue LED light into broadband green, yellow, or white light. In that case, K_{max} will at best be close to that of the blue pump light and, therefore, be less than is achievable with deep-red light. Note that, typically, the LEDs responsible for the largest fraction of the photosynthetically-active-radiation (PAR) offered to the plants emit deep-red light.

7.2.4.2 Light-Use-Efficiency

An important KPI quantifying the efficiency of plant growth relative to the integral amount of light used for growth is the light-use-efficiency (LUE). Here, the LUE is defined as the amount of sellable biomass produced during the growth period (in g plant^{-1}) divided by the integral amount of light offered to the plants (in mol plant^{-1}), resulting in g mol^{-1} as the unit of measure. Note that we count all the light emitted by the lighting installation: the light that escapes the growth layer is excluded (this gives results similar to results obtained by averaging the light as measured across an empty growth layer in the presence of a light absorbing material covering the growth layer in order to prevent spurious light reflections affecting the measurement).

For a plant factory to be economically viable, it is imperative that the LUE is as high as possible. The LUE depends on a number of factors and can be expressed by the following relation (for dry weight production):

$$\mathrm{LUE_{DW}} = l_{\mathrm{abs}}\, \alpha\, \mathrm{CUE} \times \frac{m_{\mathrm{C}}}{f_{\mathrm{C}}} \tag{7.2.5}$$

The LUE is proportional to the light utilization l_{abs} (the fraction of the incident radiation that is absorbed by the plants). It is also proportional to α, denoting the photosynthetic quantum efficiency (the quantum yield for CO_2 fixation on an absorbed light basis). Among others, α depends on the light level, spectral composition of the light, CO_2 concentration, stomatal conductance, and temperature. Hogewoning et al. [6] have addressed the wavelength dependence of α and conclude that the upper limit for α is around 0.095 for C3 plants.

CUE is the carbon-use-efficiency, defined as being the ratio of the amount of carbon incorporated into dry matter and the amount of carbon fixated by photosynthesis (a dimensionless number with a value in between 0 and 1). The CUE is related to the ratio of the daily respiration (R_{g} and R_{m}, being the growth respiration and maintenance respiration, respectively) and photosynthesis (P), as follows:

$$\mathrm{CUE} = 1 - \frac{R_{\mathrm{g}} + R_{\mathrm{m}}}{P} \tag{7.2.6}$$

Parameters m_{C} and f_{C} represent the molar mass of carbon (12.01 g mol^{-1}) and the carbon fraction of the dry weight of the plant, respectively. The value of parameter f_{C} shows minor variations among leafy vegetables and herbs: a typical value is 0.45 [7]. Typical values for the parameters discussed are listed in Table 7.2.2. (See Table 7.2.3.)

The LUE for fresh weight production of the shoots only is obtained from:

$$\mathrm{LUE_{FW}^{shoots}} = \mathrm{LUE_{DW}} \times \frac{\mathrm{DW_{shoots}}}{\mathrm{DW_{total}}} \times \frac{\mathrm{FW_{shoots}}}{\mathrm{DW_{shoots}}} \tag{7.2.7}$$

$\mathrm{DW_{shoots}}$ and $\mathrm{DW_{total}}$ are the dry weights of the shoots and the combination of shoots and roots, respectively. $\mathrm{FW_{shoots}}$ is the fresh weight of the shoots (we assume that the roots have no economic value).

Of the factors that influence the LUE, the ones that can be optimized in practice are l_{abs}, α, and the CUE. Optimization of the light utilization can be done by ensuring that as little as possible light escapes a growth layer. Next to this, transplanting can be used to ensure that during a large part of the growth period most of thes light is intercepted by the plants instead of ending up in between the plants. By means of using materials with good reflective properties underneath the plants and above the plants, the light ending up in between the plants can be recycled to some degree, improving l_{abs} even further (and as a result the LUE).

TABLE 7.2.2 Factors Affecting the LUE and Typical Values (for Lettuce Growth)

Parameter	Symbol	Typical Values	Units
Light utilization	l_{abs}	10–95	%
Quantum yield for CO_2 fixation	A	0.06–0.09	mol CO_2/mol photons
Carbon-use-efficiency	CUE	0.20–0.60	–
Carbon fraction of dry weight	f_C	0.40–0.50	–
Ratio dry weight of shoots to dry weight total = shoots + roots	DW_{shoots}/DW_{total}	0.90–0.95	–
Ratio fresh weight of shoots to dry weight of shoots	FW_{shoots}/DW_{shoots}	20–25	–

TABLE 7.2.3 Light-Use-Efficiencies (LUE) and Production Achieved for Different Crops

Crop Category	Type	Typical LUE ($g\,mol^{-1}$)	Typical Gross Production ($kg\,m^{-2}\,year^{-1}$)
Lettuce	Salanova	15–30	75–120
	Butterhead	15–20	60–75
Herbs	Basil	8–12	35–55
	Dill	6–8	25–35
	Coriander	8–10	30–40

The results relate to the fresh weight of the shoots. Lower bounds result from a crop cycle with zero or single time transplanting, whereas the upper bounds result from transplanting two or more times (not counting the transplanting after germination).

Regarding the optimization of the CUE: this amounts to minimizing respiration, relative to photosynthesis. This will be discussed next in more detail. Eq. (7.2.6) can be rewritten as follows [8]:

$$\frac{1}{\mathrm{CUE}} = 1 + g_r + \frac{m_r}{r_{GR}} \tag{7.2.8}$$

Here, g_r is the growth respiration coefficient and m_r the maintenance respiration coefficient. Values typical for lettuce are: 0.48 mol C respired mol^{-1} C fixated for g_r and 0.016 g C respired g^{-1} DW d^{-1} for m_r [8]. The quantities g_r and m_r apparently do not show large variations during a typical growth period from young plant to mature plant. The parameter that can change considerably during the growth period is the relatively growth rate r_{GR} rate (expressed in $g\,g^{-1}\,d^{-1}$). During growth, gradually, the relative growth rate will reduce (especially during and after closing of the plant canopy when the growth transitions from an exponential growth phase to a linear growth phase). As a result, maintenance respiration can become a large fraction of the total respiration, thereby reducing the CUE.

Limiting the effect of maintenance respiration on the CUE can, in principle, be accomplished by increasing the growth rate. This in turn can be achieved by increasing the daily radiation integral (DRI) offered to the plants, either by extending the photoperiod or by increasing the light level offered to the plants. Increasing the light level too much will likely result in a reduction of α (the quantum yield for CO_2 fixation) or result in the occurrence of deficiencies like tip burn: the optimum will be a trade-off.

There is also evidence that the fresh weight to dry weight ratio can be influenced to some degree by the addition of far-red (for lettuce [9]). A higher ratio implies a higher LUE for fresh weight production.

7.2.4.3 Light Utilization and Light Uniformity

Utilizing the light that is generated in an efficient manner has a large effect on the economics of a plant factory operation: not only a large effect on the production, but also on the energy use. A considerable fraction of the energy consumed in a plant factory can be attributed to the lighting system in combination with the climate control system, required for conditioning the air inside the climate cells [5].

LED lighting systems for application in plant factories typically have emission patterns resembling that of a Lambertian emitter (a source with a radiance that is uniform for all directions). Such an emitter radiates in all directions (within a hemisphere). As a result, a fraction of the rays will escape the growth layer at the sides. The fraction that escapes is determined by the ratio of the height of the LED lighting modules above the top of the plant canopy and the width of the growth layer. For example, in case of a growth layer with a width of 1.2 m and a distance from light sources to plants of 0.45 m, typically 30% of the light is lost (and therefore typically also 30% of the production potential is lost!). See also Fig. 7.2.1A Preferably, a layer width of 3 m (or wider) is combined with a distance from light sources to plants of 0.35 m (or less), resulting into light losses of 10% or less and good uniformity across the width of the layer. In practice, wide growth layers require automated plant handling and logistics. Also, maintaining a good climate for growth becomes more difficult in the case of wide layers. The possibility to apply reflective shields at the sides of the growth layers to reduce light losses is limited since this will affect the climate as experienced by the plants in the growth layers.

Light losses will be reduced in case the emission pattern of the light sources is more collimated. However, collimating the light will affect the uniformity of the light at the plant level, which is undesirable (Fig. 7.2.1B). Moreover, in case the plant canopy is not fully closed, collimating the light will result in more light ending up in between the plants, most of which will be lost. This will reduce the LUE and therefore the production. The opposite holds in case the emission pattern is broadened, resulting in a so-called batwing pattern. In practice, the optimum is a trade-off.

7.2.4.4 Effect of Transplanting Strategy on Light-Use-Efficiency

In case the plant density is low at the start of a growth period, a large fraction of the light ends up in between the plants, resulting in a low LUE. On the other hand, if the plants are spaced relatively close to each other, they have to be transplanted soon to avoid overlap.

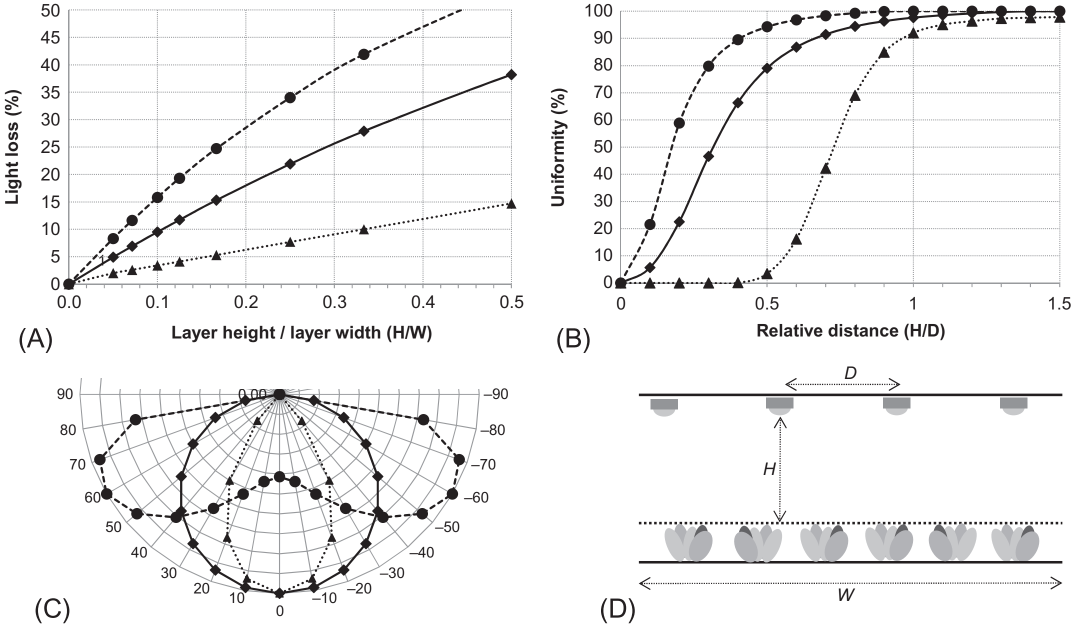


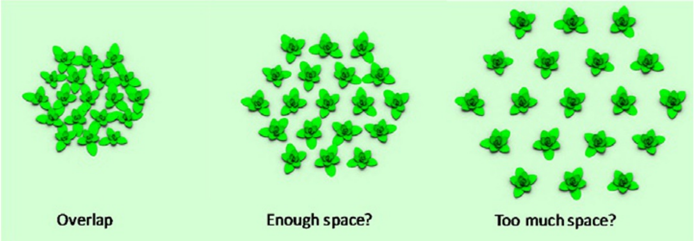
FIG. 7.2.1 Results of simulations: (A) Fraction of light ending up aside the growth layers as a function of the ratio of layer height and layer width, for various light source emission patterns. (B) Uniformity of the lighting at the top of the plant canopy as a function of the ratio of the distance of the lamps to the top of the canopy (H) and the distance between the lamps (D). (C) Polar plot of light source emission patterns. (D) Definition of dimensions. *Solid line*: Lambertian emission pattern; *dashed line*: batwing pattern (170° FWHM); *dotted line*: collimated emission pattern (60° FWHM).

Since transplanting increases the cost of labor or requires investments in automation, a transplanting strategy is needed to balance expenditures. See also Fig. 7.2.2.

7.2.4.5 Effect of Materials Choice on Light-Use-Efficiency

Another method to avoid light losses is by using materials with good reflective properties. We have developed a growth system that allows us to locate each plant (or rather the combination of plant, substrate, and plant holder) in a base plate that has a high coefficient of reflection for light (R_{floor}). Above the plants, the LED lighting modules are located. Above the modules there is a material that also has a high coefficient of reflection for light (resulting in an average coefficient of reflection R_{ceiling} for the combination of modules and reflective material). See also Fig. 7.2.2.

The fact that the materials are (highly) reflective for a wide spectrum of light makes that any light that initially ends up in between the plants will likely be reflected (diffusely or specularly, depending on the material properties) and will get a second chance of becoming intercepted by a plant. We have tested this in practice, the results of which are shown in Fig. 7.2.3.


Overlap
Enough space?
Too much space?

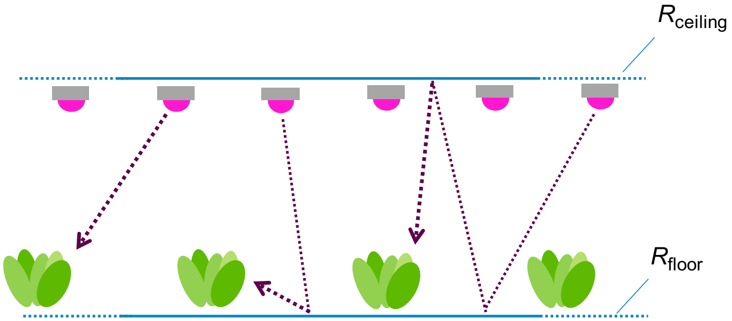


FIG. 7.2.2 Depending on the surface coverage of the plants, a fraction of the light will end up in between the plants. If no measures are taken, this light will likely be lost. A transplanting strategy is needed to balance the energy cost resulting from light being lost and the cost of transplanting (cost of labor or investments in automation). Another method to avoid light losses is by ensuring that the floor material underneath the plants has good reflective properties: light ending up in between the plants will have a second chance of being absorbed by the plants. In addition, by designing the ceiling above the plants to have good reflective properties, the light losses can be reduced further.

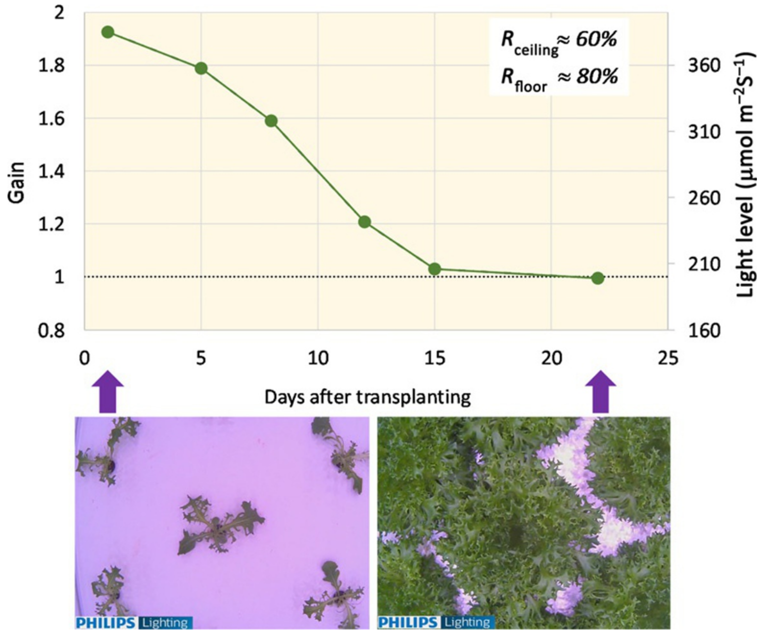


FIG. 7.2.3 Results of measurements of the gain in light level versus days after transplanting. In the experiment, $R_{\text{floor}} = 80\%$ and $R_{\text{ceiling}} = 60\%$. Initially, the light level as perceived by the plants is almost twice the light level installed.

Initially, when the plants are relatively small, most of the light will initially end up in between the plants and has a good chance to be recycled and eventually intercepted by a plant. As a result, initially the light level (irradiance) as perceived by the plants exceeded the installed light level by almost a factor of 2 (the gain factor). As is shown in Fig. 7.2.3, the light level as experienced by the plants will not be constant over time. While the plants are growing, the open space in between the plants will reduce and, hence, the effect of light recycling will become less (note that, in general, a leave of a plant reflects only a small portion of the light incident on that leave). When the plants start to overlap, most of the light will be absorbed by the leaves and almost no light will be recycled. In that case, the light level experienced by the plants will become nearly equal to the light level emitted by the LED modules (the gain factor will become close to 1).

Note that in case the floor material does not reflect any light (e.g., a black surface), light recycling will not occur (except for the few photons that are reflected by the leaves and subsequently reflect from the ceiling material). In that case, the light level as experienced by the plants will coincide with the light level installed.

7.2.4.6 Results From Growth Trials

We have performed an extensive set of growth trials to optimize the production of several crops, by optimization of the growth system, the climate settings, the irrigation and nutrient dosing, the light spectrum, the light level and timing, as well as the transplanting strategy. Table 7.2.2 summarizes the light-use-efficiency and production that we achieved for lettuce growth and the growth of several types of herbs.

7.2.5 CROP QUALITY: EFFECT OF PREHARVEST LIGHT TREATMENTS ON COLORATION AND NITRATE LEVEL OF LETTUCE

Crop quality is an important KPI that is less easy to grasp in a single number. It is challenging to improve the quality of crops grown in a plant factory while keeping KPIs such as the growth efficiency high (as expressed by the LUE, in $\mathrm{g\,mol^{-1}}$). Most research so far has been addressing quality and growth efficiency separately.

In general, quality attributes can be improved by tuning the light level, spectrum, and photoperiod. In this way, light can be used to stress the plants and invoke a response that, for example, results in red-coloration of a lettuce. In a recent study (Nicole et al. [10]), we have shown that it is possible to optimize the quality of the produce (lettuce in this case) grown in a plant factory without affecting the LUE by invoking a response to an applied light stress only during the last few days before harvest. It was demonstrated that this holds for preharvest light treatments aimed at increasing the level of coloration and aimed at decreasing the nitrate level.

7.2.6 CONCLUSIONS

In summary, we have discussed region-specific differences in food trends and the food supply chain. As a consequence, the opportunities for a profitable vertical farming business are also region-specific. We have presented a (minimum) set of key-performance-indicators (KPIs) from which business case metrics can be calculated and by which the performance of different plant factory projects can be compared, and developments tracked over time. Emphasis was on indicators relevant for estimating production yield: light-utilization and light-use-efficiency are powerful concepts to provide guidance as to how to design a growth system that makes optimal use of the light available.

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CHAPTER

8.1

Plant Factories in Taiwan

Yi-Chueh Lin

Industry technology Research Institute (ITRI)/Taiwan Plant factory Industry Development Association, Hsinchu, Taiwan

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8.1.1 BACKGROUND

The background of plant factory using artificial light in Taiwan's development can be categorized as tissue culture in orchid greenhouse cultivation as the first stage. Phalaenopsis is an important economic crop for Taiwan, which is called the orchid kingdom. The quality of Phalaenopsis tissue culture also affects the most quality of Phalaenopsis. However, orchid tissue culture environment equipment is quite different from the present plant factory using artificial light. The technological development of plant factory using artificial light in Taiwan was later than Japan, but still earlier than the other countries. We can't deny that much of Taiwan's technological research or industrial development are influenced from Japan; the plant factory using artificial light is also one of the industries.

In Taiwan academic area, it has only a few plans for the research on the plant factories using artificial light. There is no systematic research and development in Taiwan academia. Hence, you will be disappointed by the trend of the development of plant factory using

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artificial light in Taiwan by the numbers of the academic thesis. The development of plant factory using artificial light in Taiwan is mainly from the industry-based research and development, not from academic area, which is the difference with other countries. The development of plant factory using artificial light is related to the financial crisis of 2008. Taiwan's electronics industry was hit after the financial crisis, especially LED-related industries have been greatly affected. LED manufacturers in Taiwan have to find the new markets; plant factories using artificial light has become an important new market that LED could target at that time. In addition to the development of LED lighting for plant lighting, other related cultivated shelves, nutrient circulation systems, air conditioners, and so on are also being developed. During 2009–10, many LED or other electronics manufacturers have also started to set up agricultural division or related research and development team, expect to develop LED light source plant factory module, and even to focus on developing the whole plant output. This is why the proportion of LED light sources in the plant factory using artificial light is much higher than that of fluorescent lamps in Taiwan. When it comes to talking about the plant factory using artificial light in Taiwan, the general public's intuitive reaction is LED light, because this industry was developed by the Taiwan's LED-related manufacturer. Taiwan's general public began to know the plant factory using artificial light in Taipei Flower Expo 2010; LED light manufacturers exhibited a number of display cabinet-type cultivated shelves, so the public understood that the vegetables can also be planted in a confined space. “Technology Farmer” has become new direction for the Taiwanese electronics factories [1].

8.1.1.1 Taiwan Plant Factory Industry Development Association

Industrial Technology Research Institute (ITRI), the biggest research institute of Taiwan, had been interested in the industrial development of plant factory. There were some researchers attended to Japan and investigated the contents of the plant factory in 2010. They found that Taiwan could be at the advantage site to develop the technology and the equipment of plant factory. The supplied chain of semiconductor industry is developed well and has led to establish the large numbers of manufacturers-related industries such as air conditioners, clean rooms, thermal insulation materials, energy-saving lamps, control systems, sterilization technology, and electrical and mechanical equipment manufacturers. These are very close to the equipment or systems needed to build a plant factory. Therefore, ITRI and the related equipment manufacturers set up the Taiwan Plant Factory Industry Development Association in June 2010. The secretariat is also set in the campus of ITRI. Plant factory industry was just beginning; the major members are LED and electronics industry machinery and equipment manufacturers when the association began to work. The association also held a permanent speech to introduce Japan, Netherland, Israel, and other countries' agricultural materials technology and development trends. The staff of the association also hold some business matching meeting to introduce the new technology for their members. Actually, the development of plant factories in Japan has a great impact on the industry in Taiwan. The Association also called the groups to visit the plant factories in Japan yearly and also communicated with Chiba University, Tokyo Institute of Technology, Tamagawa University, and Osaka Prefectural University.

The composition of Taiwan Plant Industry development Association members from the LED manufacturers at the beginning time changed into the diversified development like the operators and the environmental control equipment manufacturers or materials manufacturers and so on. I believe this is a good development trend for the plant industry in Taiwan.

Now, Taiwan Plant Industry development Association, just like ITRI, is focused on the good connection with the Taiwan government and the industry. The Association tried to communicate with the relevant government agencies, hoping to make some changes in the laws and regulations, so that the plant factory industry could be developed more easily in Taiwan.

8.1.2 PLANT FACTORY POLICY IN TAIWAN

In Taiwan, we don't have so many large-scale plant factories that could produce 10,000 plants/day as like Japan. The reason is that the end-consumers in Taiwan are not very familiar with the vegetables produced at the plant factories. Market is not large, operators are afraid of poor sales and these make business difficult. Hence, the operators such as Japan, which produces more than 10,000 plant-based plants, are not common in Taiwan. In addition, Taiwanese government does not understand the industry of the plant factory. There is also no subsidy for manufacturers to set up plant factories. Even in different government units, the term plant factory is different. In the COA, plant factory is as the same as Japan. In the Ministry of Economic Affairs, it is called an advanced greenhouse. It defines the plant factory as a highly controlled greenhouse and is closer to the plants for both sunlight and artificial light. The COA or the Ministry of Economic Affairs currently has no subsidies for the development of the plant factory. The most subsidies were focused on several R&D projects limited to academic units and are exhausted now. If you assess the level of artificial light plant in Taiwan's development level by using the number of academic papers, you will get the wrong information about the real situation in Taiwan.

Moreover, the law about the plant factory is not clear. The situation is limited to set up the large-scale plant factory, but the advantage of plant factory with artificial light for the urban agriculture could not be archived. It is one of the main reasons that many investors want to build the large-scale plant factory, but they stop the project. Legislation restrictions also create an interesting market shift. Electronic technology manufacturers are the most industrial cluster to develop the research of the plant factory. Many companies are listed companies in Taiwan; they have factories not only in Taiwan, but also in mainland China. Therefore, it has been transformed into the base for R&D in Taiwan. If they need more space to build the plant factory, they could reform their own factories in mainland China and cultivate in the large-scale plant factory. It is very difficult to understand the technology maturity of plant factory in Taiwan from the general trend reports.

The development of the plant factory using artificial light in Taiwan is based on the enterprise's own R&D and business development. The government does not support and the academic research of plant factory is not of the mainstream and it seems not easy to develop this industry, but in fact it is not the case. The development of the plant factory industry requires the integration of many different fields. If the government actively intervenes, it will easily fall into the trap of various ministries. In the academic research of plant factory, it needs the diversity research field to cooperate together that could fit the necessities of the real market. The unilateral research team will deviate the research and development from market demand, resulting in a great gap with the actual demand; and in this scenario, it is not easy to promote the development of plant industry. The technology and market development of plant factory in Taiwan is based on market demand; it is very different from the general development of new other industries.

8.1.3 DEVELOPMENT OF EQUIPMENT AND MATERIAL OF PLANT FACTORY

The law about plant factory in Taiwan can't keep up with the development of the plant factory, so such electronic technology factories can't materialize on the planning of whole plant output as scheduled. However, these companies get the cultivation experience from the small- or medium-scale plant factory. The equipment and materials of plant factory have been improved a lot. Taking the LED plant lighting as an example, there are so many large-scale plant factories in Taiwan, but LED plant lighting has still produced a lot and exported to Japan, the United States, and other places. The LED plant lighting sales still follow the original model of the electronics industry in Taiwan, not self-brand, specialized OEM-based. Most of these LED plant lighting manufactures have set up cover 100–300 m^2 experimental plant factories in their own factory. Although they didn't expand the larger plant factory in Taiwan or stop the plant factory operation because of the reasons mentioned above, they have had many experiences to upgrade the spec of the LED plant lighting. Most of the electronic companies which have invested in the plant factory also have the LED manufacturing sector. Using the R&D experience of plant factory, the LED plant lighting of Taiwan has grown a lot with the development of Indoor Agriculture in the world.

In the other way, the plant factory in academic area is not mainstream research; it couldn't make enough of the professional manpower for the operation of plant factory. They have to develop another new system: Integrated cross-field plant factory operation management IOT (internet of thing) system. They hope this system could decrease the risk of manpower. The component supply chain of IOT in Taiwan is complete; they also started to develop the system construction that could reduce the manpower cost. These include remote operating environment control, automatic control, production forecast, personnel management, and other relevant information through the cloud computing and control; using different communication transmission systems (such as Lora or NB-IOT) to integrate and analyze the environment and production. Let the materials and equipment of plant factory developed by each plant operate more efficiently through communication technologies and systems to reduce operating costs.

8.1.3.1 Sales Channel Development

Due to the government policy and the unclear subsidy in Taiwan, the Taiwanese manufacturers are also more cautious about investing in the plant factory industry. They all start with a small amount of production and understand the habits of the consumer market before expanding their plant planning. The habit of eating lettuce in Taiwan began in the past few years. The demand for lettuce for ordinary supermarkets is relatively small. Many plant factories using artificial light produce vegetables that flow less frequently in general supermarkets and are mostly based on membership, which makes it hard to estimate the output of this industry. However, recruitment of members still takes some time. At the time of overproduction, it started to develop vegetable-related processed products or the restaurant industry to increase the added value of its vegetables, which is quite different from that of Japan's plant factories. The development of the plant factory using artificial light in Taiwan naturally forms the framework of six industries from the cultivation of vegetables, production and processing, sales and service, and brand creation. Although it is not deliberately promoted, the brand structure of its own products is enhanced. Due to frequent typhoons, the price of vegetables is not stable. Vegetables produced from plant factories become a safe and stable mode of production, and almost all vegetables from plant factory are in short supply from these 2 years.

8.1.3.2 Taiwan Manufacturer's Introduction

Since 2010, the plant factory in Taiwan has started to flourish with many companies setting up new business units for developing the plant factory and expecting new opportunities. However, the sales model (B2C) of vegetables produced by the plant factory using artificial light is very strange to the electronic technology companies who used OEM model (B2B). In the short span of 5 years, some enterprises have temporarily stopped or reduced the size of their divisions and even resell their plant factory directly to other enterprises. The following describes the potential companies for development of the manufacturers.

8.1.3.2.1 Aconpure Green Technology Co., Ltd

Aconpure Green Technology is one of the group companies of Acon Technology. Acon Technology is the group of connector manufacturers and is headquartered in New Taipei City. There are four factories in China (Shanghai Kunshan, Tianjin, Jiangxi, Shenzhen Longgang), overseas offices are Japan, South Korea, California, Vietnam, and Singapore. You may not know these cities of China so well if you are not in IT-related area. Most of the products from these cities are IT products and owned 80% of market share in the world. In recent years, Taiwan has been facing the problem of food processing safety. CEO of Acon thought it will be more and more difficult to obtain the safe food in the future. Hence, the R&D and development of plant factory was set up as a preresearch and development unit, expanded to the corporate group's business office in 2014, and established Aconpure Green Technology in 2016.

In Taiwan, there are many machinery and equipment manufacturers that want to develop the plant factory using artificial light; Aconpure Green Technology is one of them. Aconpure set up the model type of the plant factory using artificial light in the factory of headquarter. There are two plant factories in Aconpure. One is the model type in Taipei, the other one is in Shanghai Kunshan. The model type in Taipei is much smaller, only 145 m^2, the most volume of product is 365 plants/day. The products are letus, cruciferae, and baby leaf. All the fresh vegetables are sold by the membership. It is in short supply currently. Aconpure is evaluating whether to build a second factory in Taiwan. The plant factory of Kunshan is constructed in three phases, with a total area about 1200 m^2, and the maximum output is 3600 plants/day.

Not only planting fresh vegetables, Aconpure also used the freeze-drying technology in which the fresh vegetables and flowers are made into dry powder as the healthy food. It is the good example that the clean cultivation techniques were elongated to the safe and healthy lifestyle. Aconpure also develops the tourist farms in Jiangxi, China. The farm not only provides the fresh vegetables, but also cultivates the camellia and processes into camellia oil. They want to establish the food-related brand with the healthy image. Fig. 8.1.1 shows the concept shop of Aconpure in Taipei. The shop is also shown with the products of vegetables of plant factory, dry powder of vegetables and flowers, and camellia oil.

8.1.3.2.2 Unifresh Farm Co., Ltd

Unifresh Farm is a company set up by Unimicron Electronics to invest in agricultural technology industry. Unimicron is a big Taiwanese PCB (Printed-Circuit-Board) maker; Unimicron's PCB products were used in the general electronic products, like smart phone. As like most of electronic companies in Taiwan, Unimicron hopes to use the knowhow of production in factory applied to the environment-control of the plant factory using artificial light. Unifresh Farm sells these vegetables in a system that has many employees and suppliers in the factory as its main sales channels and develops its membership system. Unifresh Farm considered the marketing development and the low phases; they focused on the R&D based in Taiwan. Developing the functional vegetables is one of the strategies; they could cultivate 50 kinds of vegetables, herbs, and fruits. Large-scale plant factory using artificial light will be set up in China Mainland. Hence, there is not any plant to set up the large-scale plant factory in Taiwan. The plant factory using artificial light was set up in the Unimicron Electronics

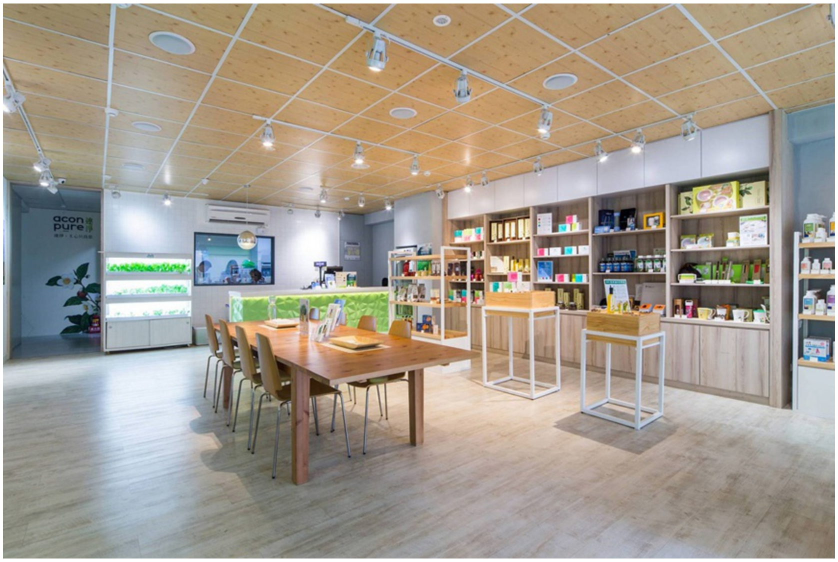

FIG. 8.1.1 The concept shop of Aconpure in Taipei.

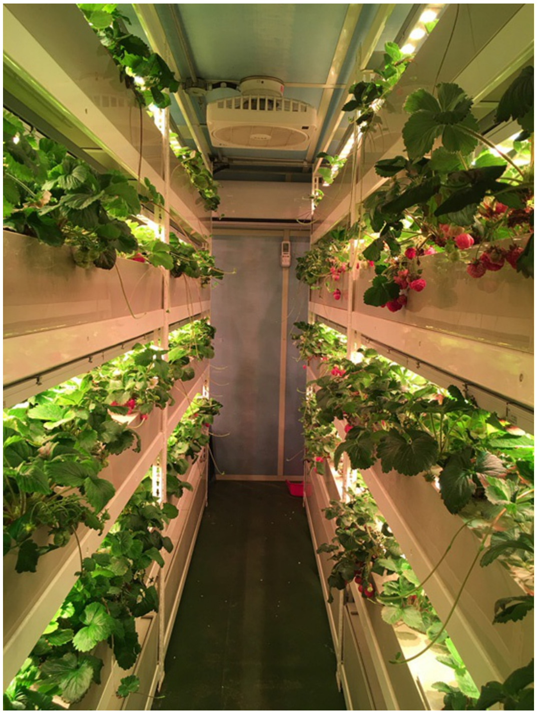

FIG. 8.1.2 The container house with cultivating the strawberry.

manufacturing factory; total area is about 500 m^2. It could produce about 1 ton per month of lettuce. Unifresh Farm also develops the technology of strawberry cultivation in container house. Fig. 8.1.2 shows the container house to cultivate the strawberry. They also apply the experience that PCB manufacturing process requires careful control of hazardous materials to develop the different cultivation technologies of the low-potassium vegetables comparing with Japan. Fig. 8.1.3 shows the low-potassium vegetables cultivating in plant factory of Unifresh Farm. Unifresh Farm not only develops the cultivation technology, but also processes the vegetables and herbs to be the fiber powder and the skin care products. They planned to transfer these planting techniques to the tourist farm in Jiangsu, China Mainland.

Unifresh Farm also invests in the trendy French restaurant and bread shop. The location is beside the factory of Unimicron. The salad in the French restaurant is using by producing from the plant factory of Unifresh Farm which is in the PCB manufacturing factory. This restaurant was reformed from an idle gas station. Unifresh Farm takes advantage of factory public safety experience and knowhow to turn hard-to-use gas station space into a trendy restaurant and, at the same time, become a gateway to promote and sell vegetables produced from the plant factory. It is indeed an innovative manifestation of the application of manufacturing factory management to the agricultural technology.

Unimicron Electronics not only invested Unifresh Farm to develop the cultivation technologies, but also developed some equipment suited for the indoor-cultivation. With the relieving of restrictions on the cultivation of cannabis in the United States, many LED lamps

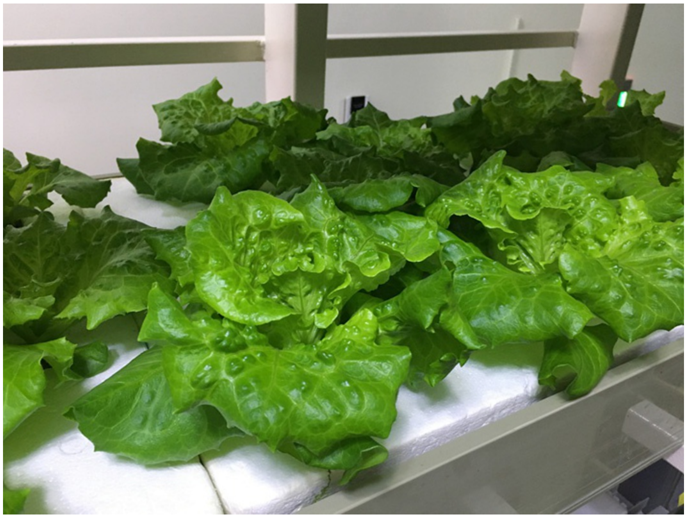

FIG. 8.1.3 The low-potassium vegetable cultivating in the plant factory of Unifresh Farm.

suitable for indoor cannabis cultivation have been developed by the group's LED subsidiary. Unimicron Electronics do not want to miss the opportunity to grow medicinal cannabis.

8.1.3.2.3 *Advanced Agritech Co., Ltd*

The parent company of Advanced Agritech Co., Ltd (AAC) is the real estate developer. The reason for entering the plant factory industry was that it wanted to make use of the real estate industry in the basement of a residential building and found that the operation of a fully artificial plant was one of the most suitable options. Vegetable sales are the most important issue in plant factory operations, in addition to cultivation. AAC has joined the fruit and vegetable wholesaler in Taiwan and introduced the knowhow from Japan's large plant factory. AAC has clearly positioned ourselves as operators and planners. Clear positioning in the industrial chain of plant factories, resource concentration, may be another new development trend of plant factories in Taiwan. AAC has been actively deployed in China and the United States. Taking advantage of Taiwan's ability to quickly adapt to customer needs, AAC wants to develop in the industry of plant factories using the artificial light.

8.1.3.2.4 *Freshintake Co., Ltd*

Freshintake established in 2012 is different from the above-mentioned plant factory development and operator; it is the developer of home-style small garden equipment. The product name is Mini Garden and the size is 80 cm(W) × 60 cm(D) × 195 cm(H); just looks like the shelve in the living room. It is expected to produce 72 strains of lettuce per month; artificial light using LED lights. Equipment is very easy to set up, only needs to have the above size of the space and a socket; the "garden" can work. Freshintake not only sells the cultivation equipment, but also develops the leasing business model. The general public is not familiar with the technique of cultivating vegetables, making it less likely to be successful in seedling and nursery. It has developed leasing models and provided the healthy vegetable seedlings to make the vegetables cultivated in the equipment look healthy at all times. It satisfied the consumer's visualization of greening and let the consumers enjoy the fresh vegetables more. Due to the easy setting and the good planting effect, many clinics, flower shops, restaurants, and other commercial facilities are used in Taiwan. Recently, Freshintake also started the development of a container-type plant factory to satisfy the needs of the clients.

8.1.3.2.5 Greenvines Co., Ltd

Greenvines was established in March 2010; the main products are organic sprouts for crops, baby leaf, and so on. Baby leaf was cultivated by using the sun and artificial light plant factory; the sprouts are cultivated by using the completely artificial light plant factory whose light source is LED. The factory area is about 330 m^2. Greenvines can produce 20,000 bags of sprouts every month. According to the different types of sprouts, the weight is also different, a bag of weight between 140 and 200 g; the distribution is focused on the high-end supermarkets and organic stores mainly.

In addition to having good technology, Greenvines also attaches great importance to the marketing of products. For the promotion of organic sprouts, Greenvines hold on a lot of lectures to educate the general public. The staff of Greenvines ran more than 100 speeches in 1 year. You can see the goods of Greenvines now in major Department stores, supermarkets, and organic health chain stores. The main products are the sprouts broccoli seedlings, purple cabbage seedling, pea seedlings, and so on.

The development of skin care products and energy soups is another highlight of Greenvines. Developed to add extractive broccoli seedling skin care products series, but also advertised in nature, no added goods shop has a good result. Energy soup is developed by many vegetables and sprouts made vegetable juice. Greenvines depended on the research and development, promotion and marketing of sprout cultivation techniques, and successfully builds a healthy and dynamic brand image. It is the important reason of the growing business for Greenvines.

8.1.3.2.6 Nice Green Co., Ltd

Nice Green was founded in 2006. It has been put into the plant factory industry in Taiwan in the early time and continued to operate and even expand its business domain. Nice Green may be the largest turnover in Taiwan's plant factory industry. Nice Green was the hydropower engineering company in Taiwan originally; the background is different with the above-mentioned electronic factory. The main vegetable distribution is based on the membership system, and it also sells in the high-end supermarket. Not only the general lettuce, finding the other functional plants and promoting the trend are Nice Green's strengths. The craze of ice plant has been created by Nice Green and it has developed special vegetables such as Taiwan jewelorchid and oyster leaf. Nice green also has freeze-dried the lettuce, ice plant, and so on and grounded to powder, as one of the raw materials for food processing, healthy food, and skin care product. The lettuce noodles, one of the processed products, become the star products other than vegetables. Hence, the processed products become another business model that increases the value of plant factory beyond selling vegetables. Nice Green also operates the restaurants mainly in Taipei. The fresh vegetables juices and lettuce ice cream are also very popular with urban workers.

Nice Green has done everything, the upstream to downstream industry chain, from setting up the plant factory, the R&D of equipment and LED lighting designed, operation, the selling of vegetables, and so on. The business model of Nice Green requires the considerable investment and patience to sustain its growth. It is one of the successful examples of the Taiwanese plant factory brands.

8.1.4 CONCLUSION

The industry of plant factory using artificial light will led the development of policy making in the future. It may be the best way for the plant factory industry to develop its own model according to its own strengths because the specialized knowledge required in the plant factory industry is too diverse and the government could not understand easily. As the plant factory industry is still in the initial stage, Taiwanese practitioners have also developed diversified business models in addition to their original planting techniques. This is Taiwan's style plant development model. Taiwan's plant factory-related practitioners take the strategy mostly as developed in Taiwan, the market in China, and materials for the world, which is very different from the country's development of plant factory industry. The manufactories of the upstream to downstream material and system of the plant factory are found in Taiwan. They also master to the trend of the market and technology of the plant factory. If you want to rapidly develop plant factory system, cooperation with the material manufacturers of Taiwan may be able to speed up the development of the system that could be a lot less wrong attempt.

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CHAPTER

8.2

Vertical Farming Development; the Dutch Approach

Jasper den Besten

Horticulture Department, HAS University of Applied Sciences, 's-Hertogenbosch, The Netherlands

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8.2.1 INTRODUCTION

The Netherlands is one of the leading countries in the world when it comes to farming in general. The country is world famous for products like seed-potatoes, tulips, vegetable and flower seeds, cut flowers, (greenhouse) vegetables and technologies in the field of climate control, water and fertilizer management, and greenhouse automation. Strangely enough, the Dutch started with plant factories with artificial light only 10 years ago, much later than the Japanese. Also, the Americans already had their visionary in this field.

Being one of the smallest and densely populated countries in the world, the Netherlands is more than self-sufficient for nontropical horticulture products. The majority of the production (€92 bln in 2017) is exported [1,2]. Therefore, the consumer prices on the Dutch market are

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low, self-sufficiency is no issue, and food-miles are limited. In greenhouses in the Netherlands, most crops grow out of the soil in a recirculation system for water and fertilizers, climate is taken care of, and pests and diseases—if they occur—can be managed biologically. Few chemicals for crop protection are used. With top and interlighting, production can be realized year-round. With all these technologies, greenhouse crops have year-round high yields and top-quality. The cultivation system is quite sustainable already. Food safety finally, in general, is no issue. The "big" cities like Rotterdam and The Hague are very close to greenhouse concentration areas and even the distance to the capital city, Amsterdam, is limited to 50 km.

The Dutch continue to improve greenhouse production significantly. By using all modern technologies, tomato production in kg/m^2 per year almost tripled in the period 1980–2017 in greenhouses without artificial light. In greenhouses with top and interlighting, the magic boundary of 100 kg/m^2 per year has been reached in 2015 in the GreenQ Improvement Centre Bleiswijk in 2015 [3] and production is expected to increase even further.

The names "plant factory" or "plant factory with artificial light" as used in Asia are unknown in the Netherlands. Greenhouses with and without artificial light are not considered being plant factories and consumers do not really know the name "plant factory." Probably, "vertical farm" and (high-tech) "city farm" are mostly used for growing plants in multilayer systems with LED-light only.

So far, there is no reason for vertical farming in this typical agricultural country. Yet, the Netherlands has high-level education, scientific and applied research, and suppliers in the field of vertical farming. In this article, after a short overview of the Dutch history in vertical farming, the Dutch approach of vertical farming will be explained and important vertical farming challenges will be discussed.

8.2.2 OVERVIEW OF VERTICAL FARMING DEVELOPMENTS IN THE NETHERLANDS

Farming in multilayers or vertical farming was first used in indoor white mushroom production. From the 1950s, mushrooms grow in a special compost covered with casing soil, in four or more layers in shed-like, climatized buildings. The white mushrooms grow in the dark. Because of scaling up in the Netherlands and migration of mushroom production to East-Europe, many of these so-called mushroom-cells are empty nowadays. So far, they have not been used for vertical farming of autotrophic food crops yet, except on experimental scale.

Another type of multilayer production system is in use for the typical Dutch and Belgian chicory production. The roots of the crops grow during the summer in soil in arable farms. The roots are stored and used year-round for the production of the chicory, *Cichorium intybus* (a leafy vegetable). For the production of the vegetable, the roots are put in a stacked container system with water and plant nutrition. The chicory vegetable grows in the dark, so that the color is white to yellow and the taste is not too bitter. In the production system, eight or more layers are used.

The first vertical farm with artificial light in the Netherlands was a project of the combination of the technical companies Schulte & Lestraden. This was in the 1980s in Roermond. In the farm tomatoes, chrysanthemums, tulip flowers, lettuces (Fig. 8.2.1) as well as mushrooms were

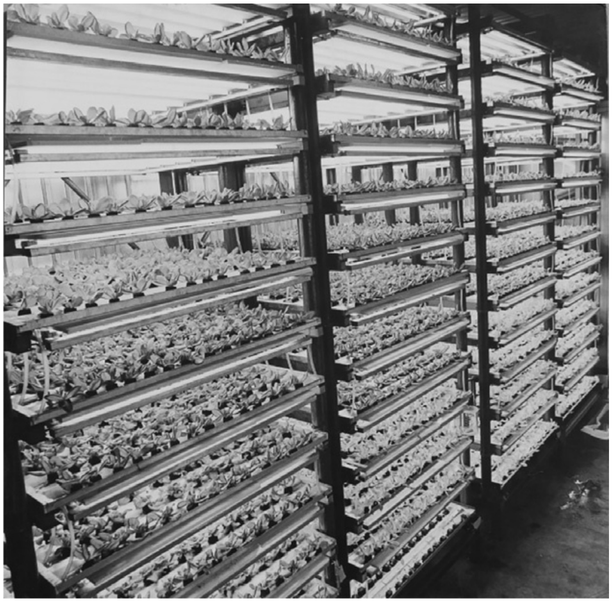


FIG. 8.2.1 Multilayer lettuce production at Schulte & Lestarden, Roermond, The Netherlands in the 1980s. *Courtesy of Schulte & Lestraden and Nivola.*

grown, partly in greenhouses where the heath of the cooling was used and partly indoor in just one or multilayers (lettuce heads). Because of the inefficiency of fluorescent and high-pressure sodium lights in those days (absence of LEDs for horticulture), the heath produced by the lights was high and the cooling so expensive, that the project stopped after a few years.

It took more than 20 years before, in 1998, vertical farming was used again by "Tuinderij Bevelander," a company specializing in fresh herbs, for the year-round production of chives (Fig. 8.2.2). The cultivation of chives is biannual. In the first year, starting from seed, the plants are grown in fields, harvested in autumn, kept at low temperature to overcome winter rest, and planted in a vertical farm to grow new leaves. The vertical farm started with fluorescent lights in a system of five layers and uses LEDs since 2015.

The first horticulture LEDs in the Netherlands came in 2008 and rapidly improved in quality and energy efficiency. In 2009, trials in greenhouses and in closed systems started. The first vertical farm of significant size ($>5000\,m^2$) was and still is a seven-layer system for the (extended) raising of young lettuce plants at Deliscious Lettuce in Beesel. The last part of the lettuce cultivation takes place in a high-tech greenhouse.

In an old industrial building in Eindhoven, "Duurzame Kost" started an aquaponics system for the production of fish and vegetables and herbs in 2016. Although the farm is inside a building, it is a one-layer hydroponics system with toplights that need about 1.5 m between lamp and crop. The products are sold locally to consumers in the food market in this Veem-building and to local restaurants.

Because of the fact that the cost prize for greenhouse products in the Netherlands is so low, the business case calculation for Dutch-based vertical farms is a challenge. Produce from a vertical farm in general is not cheaper than from greenhouse production and, in The Netherlands, it will be difficult to explain to consumers why they have to pay a higher price and, to producers, why they have to invest so much per square meter footprint.

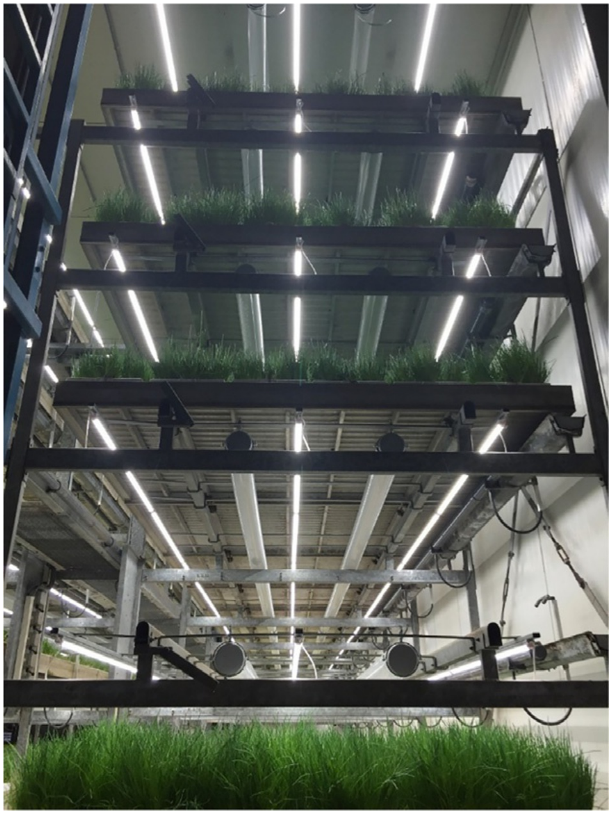


FIG. 8.2.2 Chives production (2018) in the vertical farm of Bevelander, Achthuizen, The Netherlands. *Courtesy Bevelander.*

Nevertheless, the new vertical farms like GrowX Amsterdam opened in 2017. In these relatively small city farms, often a combination of niche products is made in a sustainable system for local use. Turn-over also comes from other activities like from education, from advise and consultancy, from sales of the systems, and from employing staff with a so-called distance to the labor market.

The biggest farm in the Netherlands will be opened in 2018 in Dronten by Fresh-Care Convenience (Staay Food Group). This vertical farm for lettuce and other leafy vegetables is located next to the production lines of fresh meal salads for a big supermarket chain. With the start of the production, finally The Netherlands will have its first commercial vertical farm for fresh food production of significant size. Apparently, the Staay Food Group defined a series of advantages of this production system for the making of meal salads.

8.2.3 AGRICULTURAL EDUCATION

Agricultural education has always been important and, especially after the second world war (1940–45) when people died of hunger, the government stimulated agriculture education (and research and extension). A description of the Dutch education system, in general, is available from Nuffic [4].

The Netherlands has three major types or levels of agricultural education:

1. Vocational training (UK national diploma level) for staff that normally work in agricultural production and can lead a team of workers. This type of education is very practical and includes a lot of internships in primary production. The operational management of a vertical farm (on the work floor) can be done by graduates of this type of education.
2. Bachelor level education is offered by former polytechnics, now named Universities of Applied Sciences. Since 10 years the BSc course in Applied Biology delivers graduates that are searching for applied research jobs in agriculture. The education is very applied and graduates easily find jobs in the industry worldwide, only a minority of the graduates continue with studies on Master of Science level. Most graduates have jobs in agriculture business management (running a farm or a farm unit) or in agricultural business (international trade, marketing, sales). A minority has jobs in applied research in the ancillary industry like seed companies. Graduates with this applied bachelor degree are highly appreciated by the industry. The Netherlands has agricultural universities of applied sciences in Delft (InHolland), Dronten (Aeres), 's-Hertogenbosch (HAS), and Leeuwarden (Van Hall Larenstein). Graduates play an important role in the development of vertical farming in The Netherlands.
3. University level education in agricultural sciences is limited to Wageningen University, although several other universities with a biology-program are involved in plant research. Wageningen University attracts a lot of international students in the (MSc) program of Plant sciences, next to Dutch students. Part of this student population entered with a bachelor in applied plant sciences. Graduates of Wageningen can be found in jobs in agriculture worldwide.

Compared to the importance of Dutch horticulture, the student numbers in courses in this field are rather limited. Although both Wageningen and the bachelor level universities have increasing student numbers, the number of agriculture students is limited in relation to the number of actual and expected jobs on this level.

The Netherlands has no complete bachelor or master courses in vertical farming; vertical farming is a regular part of the horticulture and applied biology courses. Both Wageningen University and HAS University have short courses for "vertical farming"; HAS University has a short course in "hydroponics for high-tech horticulture," in cooperation with research center Zwaagdijk. HAS University also offers an English-taught online course in "growing without daylight."

8.2.4 SCIENTIFIC AND APPLIED RESEARCH

Most of the agricultural research in the Netherlands is carried out by Wageningen University and Research (WUR) Institutes. The Wageningen University research is scientific; research in the research institutes belonging to WUR is more applied, like in the WUR Bleiswijk research location, in the middle of one of the horticulture centers.

Applied research in universities of applied sciences is becoming more important since the Dutch government decided a decade ago that these universities should play a bigger role in applied research, development and innovation, and in knowledge transfer to the industry. In all bachelor level universities, so-called "lectors," the equivalent of scientific university professors, work in the field of applied knowledge development and applied research.

HAS University of applied sciences started applied research activities in vertical farming in 2009 together with partners Croppings (later PlantLab) and Philips. PlantLab scaled up with partners o.a. Syngenta, HAS University continued with more open innovation together with Philips and a private research institute called Botany in a joint research facility for vertical farming "BrightBox-Venlo." In applied research, underlaying pathways or mechanisms often are not included. For application of new knowledge, this is not necessary.

Although the credits for the technology of vertical farming probably belong to the Japanese university professors and researchers and we thank the promotion of vertical farming in the western world to the Americans, the Dutch are excellent in making high-tech horticulture to a success. Because of business case calculations, the Dutch try and answer very practical questions like why build a vertical farm if you can have controlled environment agriculture in one layer with less investments; why take care of temperature with a variation of max. 0.1°C while greenhouse can have differences of more than 5°C; why bring people to the plants if you can bring the plants to the people. In all these questions, the financial consequences are calculated.

Although the Dutch do not run a single large vertical farm for fresh vegetable production yet, there are a dozen places where applied vertical farming research can be carried out.

8.2.5 THE VERTICAL FARMING SUPPLIERS

The Netherlands has a wide range of companies supplying materials for high-tech farming and can build complete vertical farms and companies that can advise. These companies supply directly or via agents to the bigger commercial growers and via agents and shops to small farms, hobbyists, and startups.

More than 30 vegetable breeding companies are active in leafy vegetables and the bigger ones are starting with variety development for vertical farming; most of these companies already have developed varieties for hydroponics. For soil, "glue plugs," and other substrates from paper pulp to stone wool, a series of internationally operating companies offer a wide range of products, also for vertical farming.

Again internationally operating fertilizer suppliers offer both mixes and single soluble and liquid nutrients and, for less than 50 euro laboratories, do the analyses including advice. Also for climate control, fertilizer management, gutters, ebb-and-flow systems, cultivation gutters and tables, LED light, sowing, grading and packing automation, and transport, many companies are active in not only sales, but also in service.

The higher the tech-level of the industry, the more important it is to have these services close by. Vertical farming in this small country is relatively simple compared to high-tech-rich but horticulture-poor parts of the world where vertical farms could play a bigger role.

Next to all these suppliers, because of the export position of Dutch horticulture, logistics, marketing, sales, export, and international trade are highly developed as well. Products can arrive at the door of customers in neighboring countries within a day and at the other end of the world in 2 days.

8.2.6 APPLIED RESEARCH PROJECTS

Applied research in Universities of Applied Sciences is often carried out by graduating students under supervision of research staff of the lectorate. The sponsor of these projects is the industry and all outcomes are owned by the industry. Unlike scientific research, publications are not written and no presentations are given on symposia like LightSym. Reports are in Dutch and cannot be found via desk research. The results are included in the curricula of courses in horticulture and applied biology, shared with the industry in courses both on location and online and shared in further research with the industry.

The type of applied research projects is divers. It may concern breeding, propagation, and production and may include a wide range of objectives from developing protocols for the testing of bolting in leafy vegetables and life cycle reduction for breeders, via high-speed propagation for the introduction of new varieties of slow-propagating vegetatively propagated crops, to variety trials under LED-light only and light recipe development for quantity or quality. In the following, some examples of this research will be discussed.

8.2.6.1 Plasma-Activated Water

Market prices for organic produce are higher than for standard produce. Although vertical farming products are not treated with (crop protection) chemicals, due to the use of nonorganic fertilizers, the product cannot be labelled as organic (Eko-label) in the Netherlands. About 50% of the nutrients both in weight and volume is nitrogen. Replacing nitrogen from traditional fertilizers by one that would be accepted under the Dutch organic label is the first challenge. Organic fertilizers may be a solution, but from a technological and control of fertilizer availability point of view, the mimicking of nitrogen deposition in nature, as plasma-activated water [5], is preferred.

In a climate cell, nitrogen in the fertilizer solution was completely replaced by nitrogen in plasma-activated water (PAW) in a simple setup with young cucumber plants in small stone wool plugs in a water cultivation system. No significant difference was found between the standard fertilizer solution and the one with nitrogen from plasma water (Fig. 8.2.3.).

A challenge is the search for plasma-activating machines that give a constant and high enough level of NO_3^- for use in hydroponic systems.

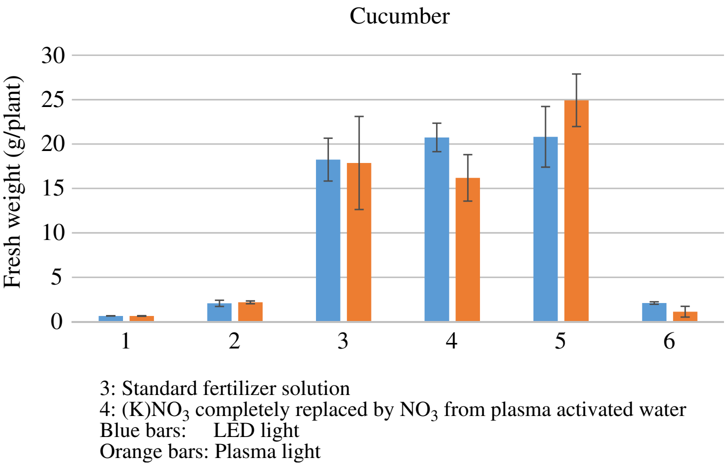
8.2.6.2 Phytochemical Content

Human health becomes more important and phytochemicals, like flavonoids, play an important role. Biocontent can be influenced by many external factors, light being one of them. Blue light is a crucial part of most light recipes and also plays an important role in the production of flavonoids. Although absence of blue light gave significant lower total flavonoid levels, no differences were found between the treatments with different blue light levels.

8.2.6.3 Life Cycle Shortening of Spinach

Spinach is normally grown in soil in fields, but the produced quantity and quality can fluctuate a lot over the year due to seasonal and other climatical influences. Especially, baby leaf

FIG. 8.2.3 Cucumber young plants under LED and plasma light in a climate cell.



spinach is an interesting product for vertical farming. The production of enough kilos per square meter per day to make it profitable is not easy. A search is ongoing to the right variety, climate, light, and cultivation system. One option to improve the yield is to have multiple harvest. Bolting can be a problem though, so part of the research concentrates on the life cycle of spinach. Breeders want to know how to shorten the life cycle in order to speed up the breeding, while growers need information about the postponing of flower induction and realization. Fig. 8.2.4. shows spinach flowering 28 days after sowing. Far-red light plays an important role in early flowering.

8.2.6.4 Shortening the Basil Hypocotyl with Light

The hypocotyl length of basil herbs in a vertical farm can be quite high, so that plants can fall over when they are bigger. Several light strategies are applied on basil (*Ocimum basilicum* "Marian"). In general, hypocotyls are taller when the daily light intergral (DLI) is lower. From Fig. 8.2.5. it is clear that the hypocotyl length becomes shorter by adding more red light. In the same trial, far-red gave a longer hypocotyl.

8.2.6.5 Growing "Without" Substrate

In hydroponic systems, limited quantities of substrate are used, often just for sowing and young plant raising. Although soil is a perfect substrate for this purpose, because of hygiene considerations, other substrates have the preference. Vertical farms use several types of substrates to replace soil, varying from glue plugs, coco peat pellets, stone wool, and foam. Another option is the use of paper pulp, already used for the production of microgreens in small containers with a very high plant density.

An interesting idea is to see if also crops that grow in lower densities can grow to harvestable stage in this medium. Although trials are ongoing, there are some interesting results with lettuce, mustard, and radish. These crops are sown in small strips of paper tissue (Inserotech)

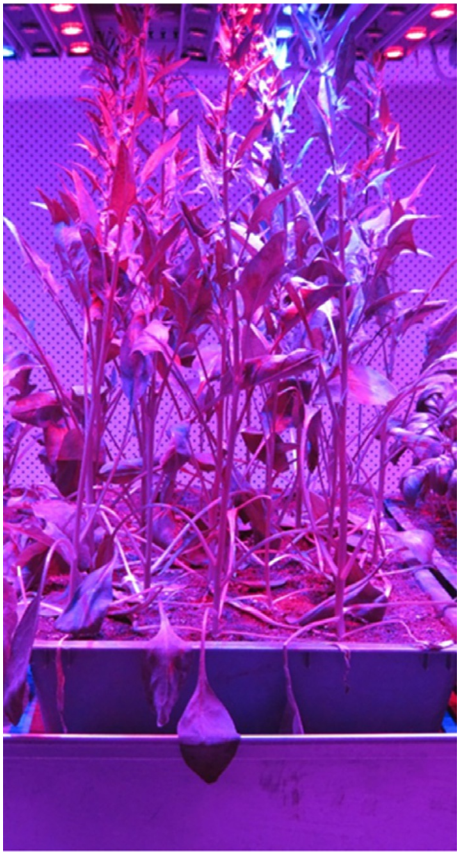


FIG. 8.2.4 Flowering spinach 4 weeks after sowing.

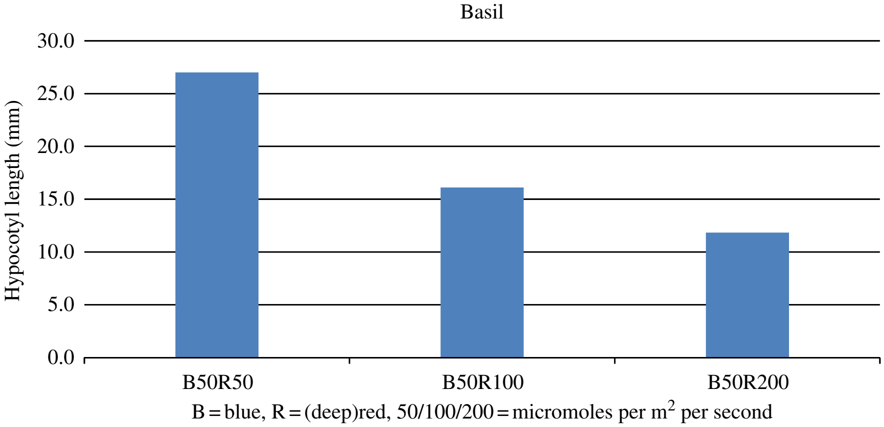


FIG. 8.2.5 Effect of increasing *(deep)red* light on hypocotyl length of Basil (*Ocimum basilicum* "Marian").

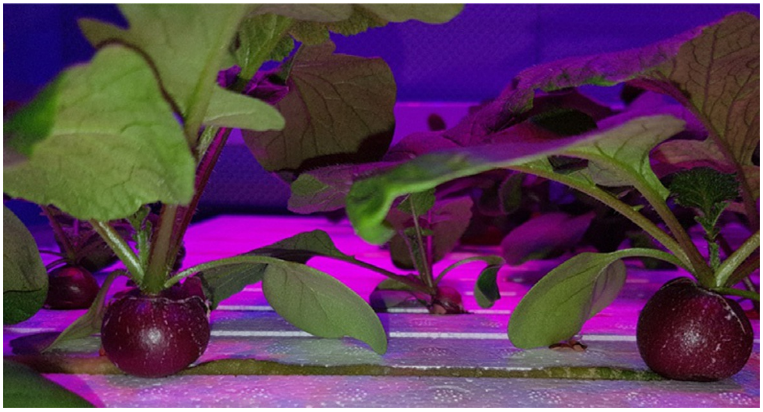


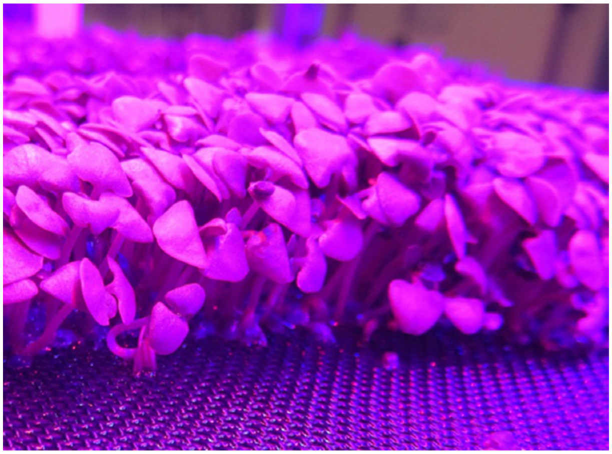
FIG. 8.2.6 Radish (Hazera number) on (Inserotech) paper tissue in (Hortinov) floating panels in a deep flow system, 18 days after sowing.

fixed in Canadian Hydronov floaters for deep flow systems. In this system, only a very small (5 mm) opening is available for the seeds, seedlings, and full-grown plants.

By adjusting the paper strip height, all crops can be grown to full-grown stage, although the lettuce stem/root top, because of its diameter, can easily break the floater structure. Mustard and radish can be grown to harvestable stage without damaging the floater. It is possible to reduce the use of substrate to a minimum in this system. Fig. 8.2.6. shows a picture of harvestable radish.

Another option is to grow plants completely without substrate. There are several initiatives to work out this system, but it is a puzzle to develop a system that holds plants well even when the stem diameter expands, does not pinch off the transport via stem and roots, and is easily cleaned and recirculated. An interesting option is to grow on a net in combination with ebb-and-flow (at the start) and deep flow at the end of the cultivation (Fig. 8.2.7.).

FIG. 8.2.7 Basil cress on a net, without any further substrate.



In radish trials with this system under Philips production modules (generation 1) giving 240 μmol/m^2/s, a radish harvest of more than 400 g/m^2 per day (leaves and tuber fresh weight) is feasible in cultivation periods from seed to harvest in less than 20 days.

8.2.6.6 Light-Yield Relation

In trials, more light resulted in more production, but not in an expected 1:1 ratio. This ratio is often discussed before [6]. One percent of (more) light resulted only in 0.25%–0.75% more (dry matter) production. It was seldom possible to measure root weight, because the harvesting of clean, dry, and soil-free roots was too complicated. The search for a medium that would allow normal growth and root harvest finally resulted in sand being the best medium. One percent light gave 0.6% more yield (dry matter) in the leaves and stem parts of the plant and 1.6% more yield of the roots. So after all, with 1% more light, the total dry matter went up with about 1%. It shows how important it can be to do total yield experiments in physiological research. In applied research, often only harvest of marketable parts is perceived.

8.2.7 CONCLUSION

Although there is no direct need for vertical farming in The Netherlands, because of the country's history in high-tech horticulture, the Dutch are also active in vertical farming education, (applied) research, extension, and supply. There is a strong link between these four activities. The combination of green and technical knowledge and experience in this field, plus realistic business case calculations, may lead to vertical farms being a new export product next to high-tech greenhouses. Many vertical farming issues have been researched in or with the industry so that they can immediately apply the results, but are not published.

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CHAPTER

8.3

Plant Factories in Japan

Kenji Nakamura[*], *Hiroshi Shimizu*[†]

[*]Environment Monitoring Dept., ESPECMIC Corp., Neyagawa, Japan

[†]Graduate School of Agriculture, Kyoto University, Kyoto, Japan

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8.3.1 HISTORICAL BACKGROUND OF PLANT FACTORIES IN JAPAN

Research and development of a plant factory with artificial light (PFAL) was started by universities, experimental research institutes, laboratories of major companies, etc. from the 1970s to the early 1980s in Japan. After that, following the exhibition of the plant factory at the Tsukuba Expo in 1985, many different industries such as electric power companies in Japan, food companies, steelmakers, oil companies, household appliances, and environmental equipment enterprises have entered the plant factories one after another from the late 1980s to the early 1990s. At this time, not only PFAL, but also work of a supplemental light type plant factory attracted attention, and the European type greenhouse horticultural technology was adopted, and the system development which combines original robot technology and environment control technology was actively carried out. In the latter half of the 1980s, a farming venture company aiming to operate an artificial light type plant factory on a sales basis appeared and attracted attention (Fig. 8.3.1).

In the early 1990s, the Plant Factory Association (currently Japanese Society for Agricultural, Biological and Environment Engineers and Scientists), as an academic organization promoting the practical use of plant factories, and Plant Factory Promotion Association (currently Association of Indoor Farm), where companies gather and promote plant factories,

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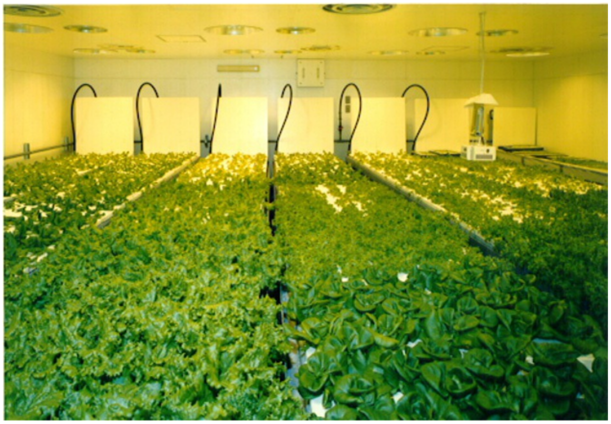
FIG. 8.3.1 Typical PFAL in Japan in the 1980s.



were established one after another. With these triggers, the "Ministry of Agriculture, Forestry and Fisheries" started a subsidized project targeted at plant factories; plant factories aiming for commercial operation were established primarily by farming groups at several pace every year throughout the country.

Most plant factories constructed in the 1990s adopted high-pressure sodium lamps and metal halide lamps as artificial light sources and devised to effectively utilize the plane without multistage. Among them, an artificial light type plant factory "TS Farm" developed by Kewpie Co., Ltd., which manufactures and sells mayonnaise and dressings, is a typical example (Fig. 8.3.2). The TS farm is a spray system in which cultivation panels are assembled diagonally in a triangle shape and nutrient solution is sprayed from there. By building up the panel, it is about 1.5 times more cultivation-efficient than the case of installing the panel on the flat surface.

Container type plant factory which used the marine transport container recently found all over the world has also been developed and put into practical use by Tabai Espec (currently Espec) in the early 1990s (Fig. 8.3.3). Twenty- or fourty-foot standardized marine transport

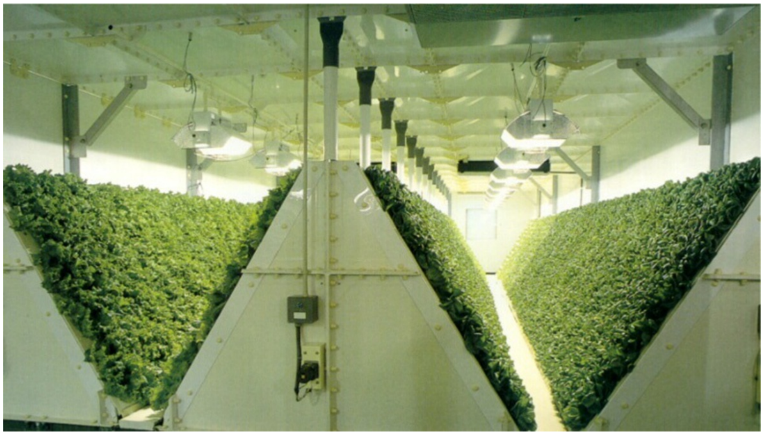


FIG. 8.3.2 TS farm by Kewpie Corp.

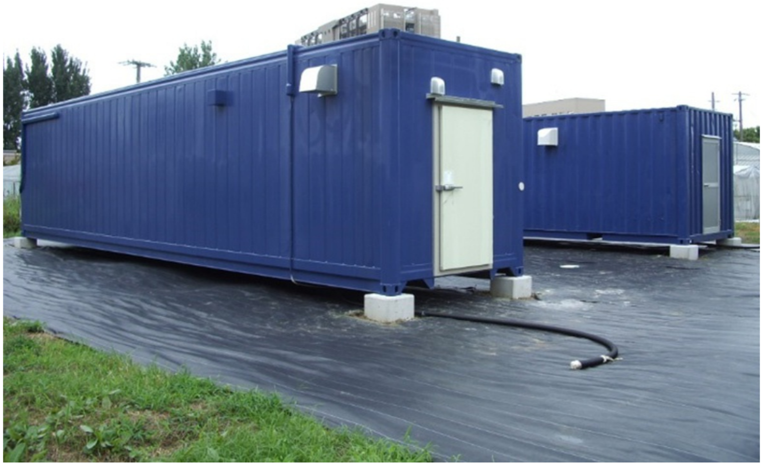


FIG. 8.3.3 Container type plant factory.

container was used, and it was installed in the outdoor space to select the installation location and was introduced with the concept that vegetable cultivation is possible as soon as electricity and water are connected.

In the 2000s, the efficiency of fluorescent lamps advanced and multistage plant factory which adopted fluorescent light and liquid crystal backlight (Fig. 8.3.4) as light source became main stream instead of high pressure sodium lamp. Plant factories where the production volume of leafy lettuce exceeds 1000 heads per day have also appeared.

In 2009, the Ministry of Economy, Trade and Industry and the Ministry of Agriculture, Forestry and Fisheries began promotion of the plant factory. A compact type PFALs were set up at the lobby of the Ministry of Economy, Trade and Industry, stations, airports, shopping streets, and theme parks which are open for all to see, and the awareness of the plant factory

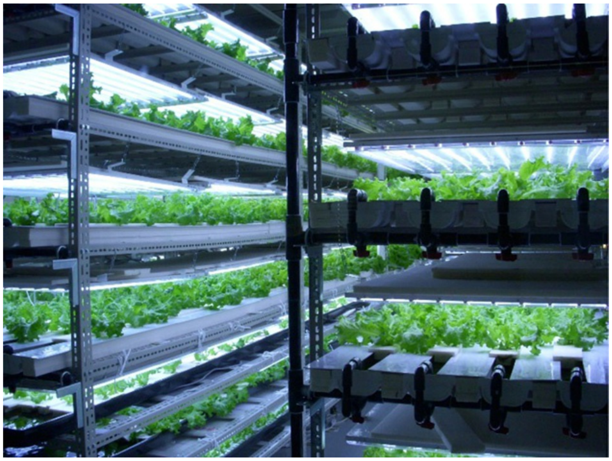


FIG. 8.3.4 PFAL with liquid crystal backlight as light source.

FIG. 8.3.5 Plant factory for exhibition.

increased at a stroke (Fig. 8.3.5). And this movement is the foundation that the plant factory boom in Japan continues to present [1].

8.3.2 LED LIGHT SOURCE AND PFAL IN JAPAN

In the 2010s, LEDs began to popularize, and LEDs have become the main light source of PFAL instead of fluorescent lamps since the mid-2010s. Early-stage LEDs had low luminous efficiency and many were not accompanied by waterproofing or drip-proofing performance, but these drawbacks were also improved. The average lifetime as a light source is also about 40,000 h; the power consumption also becomes about 1/2 of that of a fluorescent lamp, leading to a reduction in running cost.

Also, the type of LED light source was commercialized as an LED light source dedicated to raising plants having wavelength peaks of red(R) and blue(B) suitable for growing plants. The characteristic feature among these is a cultivation method of alternately irradiating red and blue at a certain time ratio developed by Showa Denko. In certain leaf lettuce, it is reported that the cultivation method using this RB light source accelerates the growth speed (Fig. 8.3.6).

On the other hand, a white LED light source having a pseudo white wavelength characteristic by coating a phosphor on a blue LED is adopted as a light source of PFLA, which produces many leaf type lettuce (Fig. 8.3.7). Many of them are of the 40 W type straight-tube shape.

The luminous efficiency of the LED element is improved, and the average PPFD on the cultivation surface can also be more than that of the fluorescent light. In addition, because

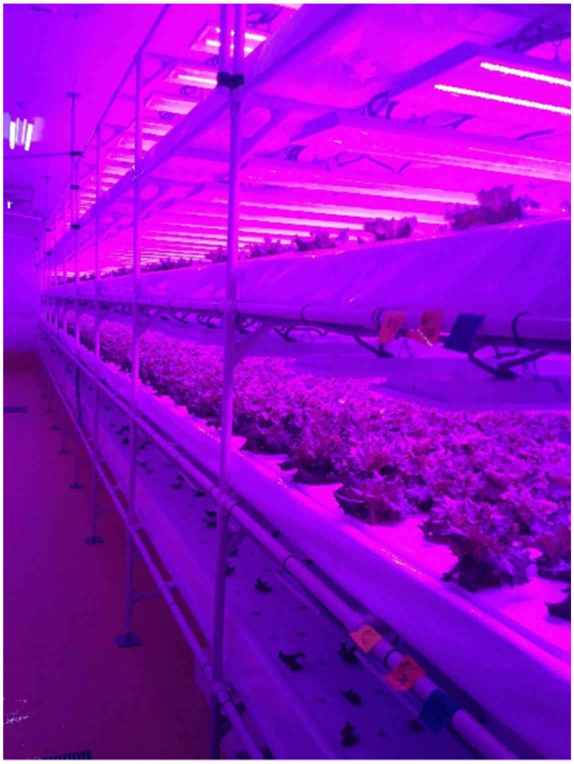


FIG. 8.3.6 PFAL with RB light source.

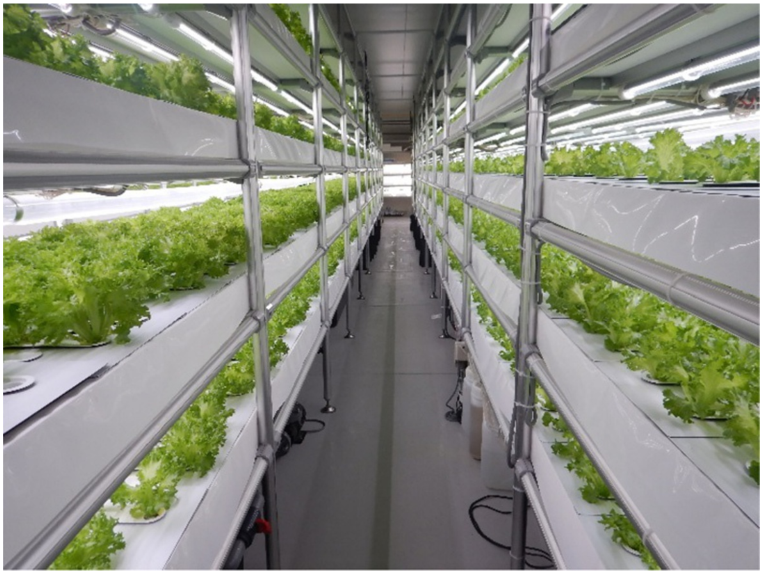


FIG. 8.3.7 PFAL with white LED.

it is relatively inexpensive, there are many cases that are adopted in PFALs of scale exceeding 10,000 heads of lettuce per day which has been recently built in Japan [2].

8.3.3 A PFAL FOCUSING ON VEGETABLE FUNCTIONALITY

The characteristic of the vegetables produced at the PFAL is that it is a pesticide-free and low-bacterial clean vegetable. However, PFAL vegetables with high production costs are not superior to open land and general hydroponic vegetables with no pesticide or low bacteria alone. Low-potassium lettuce, which Professor Ogawa of the Akita prefectural university developed, is just the focus on vegetable functionality. Since patients taking dialysis such as diabetes are restricted in potassium intake, it was noticed that raw vegetables can be eaten by suppressing potassium contained in vegetables considerably. Since patients taking dialysis such as diabetes are restricted in potassium intake, low-potassium lettuce has attracted public attention as raw vegetables can be eaten by suppressing the potassium value contained in the vegetables considerably.

Contrary to this low-potassium lettuce, supplement vegetables raised mineral components such as magnesium contained in vegetables are also put to practical use in joint development of DHC Corp., ESPEC MIC Corp., and Kyoto University. By adding deep sea water (DSW) containing abundant minerals to a nutrient solution for cultivation at a certain concentration, improvement of the content of natural mineral components in plants was succeeded.

It has been reported that the ratio of Ca and Mg in the meals eaten on a daily basis is very relevant to health. Especially, it is known that as this ratio increases, the heart disease increases. This research team succeeded in reducing the Ca/Mg ratio from 1.77 to 1.13 by adding DSW to the nutrient solution. Furthermore, vitamin C is 1.6 times, vitamin B6 is 1.8 times, biotin is 1.5 times optimizing the addition condition of DSW.

8.3.4 FUTURE PFAL IN JAPAN

There is a sense that the plant factory boom in Japan is still going on, but in recent years there are few examples of small businesses, etc. and of different industries participating as new businesses are decreasing. It was said that the scale that can be profitable at PFAL in Japan is the production of leaf lettuce 1000 heads per day about 2010, and that it is 5000 heads or more in a few years, more recently 10,000 heads or more. In PFLA with more than 10,000 heads lettuce production per day, construction costs will be close to 1 billion yen if it is built from building construction.

In fact, it is getting hard to enter easily unless it is a financially powerful company. Naturally, production cost will also be reduced if the production scale is over 10,000 heads per day, so shipment will increase not only for mass merchandisers but also for professional use.

Meanwhile, small- and medium-sized plant factories that operate closely with local communities are doing well. There are also PFALs where multiitem of vegetables other than lettuce are supplied to local hotels and restaurants in accordance with their needs, and employees who operate handicapped persons as employment facilities for persons with disabilities hire. Not only pursue economic efficiency on a large scale, it is worth noting that styles that closely contact the local area and make use of the characteristics of the local area.

In this way, the Japanese PFAL was put to practical use ahead of the world, and it is progressing step by step through trial and error. We believe that it is our mission to involve PFAL in sharing technology with each other and delivering safe and secure vegetables to people in a situation where PFALs are spreading all over the world [3].

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CHAPTER

9.1

VERDIR (Enhancement of the Environment Through Sustainable Rehabilitation and Responsible Innovation)

Bach Kim Nguyen, Eric Haubruge
University of Liège, Liège, Belgium

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9.1.1 INTRODUCTION

VERDIR is an environmentally minded urban agricultural project of the University of Liège. It can be described as an innovative concept of ecosystem-based production of foodstuffs and nonfood items of vegetable origin based on innovation.

Plant Factory using Artificial Light
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The concept of eco-system is a double fold reality, both internal and external:

- Internal: putting in place an exchange network between production units so as to ensure the self-sufficiency and self-reliance of the operating entity, in terms of energy consumption as well as the development of available spaces, recycling of waste (inputs and by-products), and water management.
- External: exploitation is an integral part of a self-sustainable system, a link in a wider chain of ecological value. It stretches from primary production units to consumer services, through processing and distribution thanks to the use of short routes and the by-products from several chain activities.

The urban component refers to the exploitation of disused and abandoned spaces in urban areas and their outskirts (industrial zones) so as to make better use of proximity farming.

VERDIR is a project for urban agriculture: it is about growing and distributing food and nonfood plants directly to the urban market, in and around an urban area. Urban agriculture is a subsector of the environmentally minded urban agriculture as previously described.

In practical terms, the concept behind VERDIR aims at developing a sustainable production system through optimizing unused assets (decommissioned industrial sites, energy by-products…).

Production systems mainly imply:

- The production of living vegetable as food;
- The optimization of high-value-added molecules obtained from plant biomass.

The VERDIR project aims at transforming environmental threats into opportunities to generate economic, environmental, and social value.

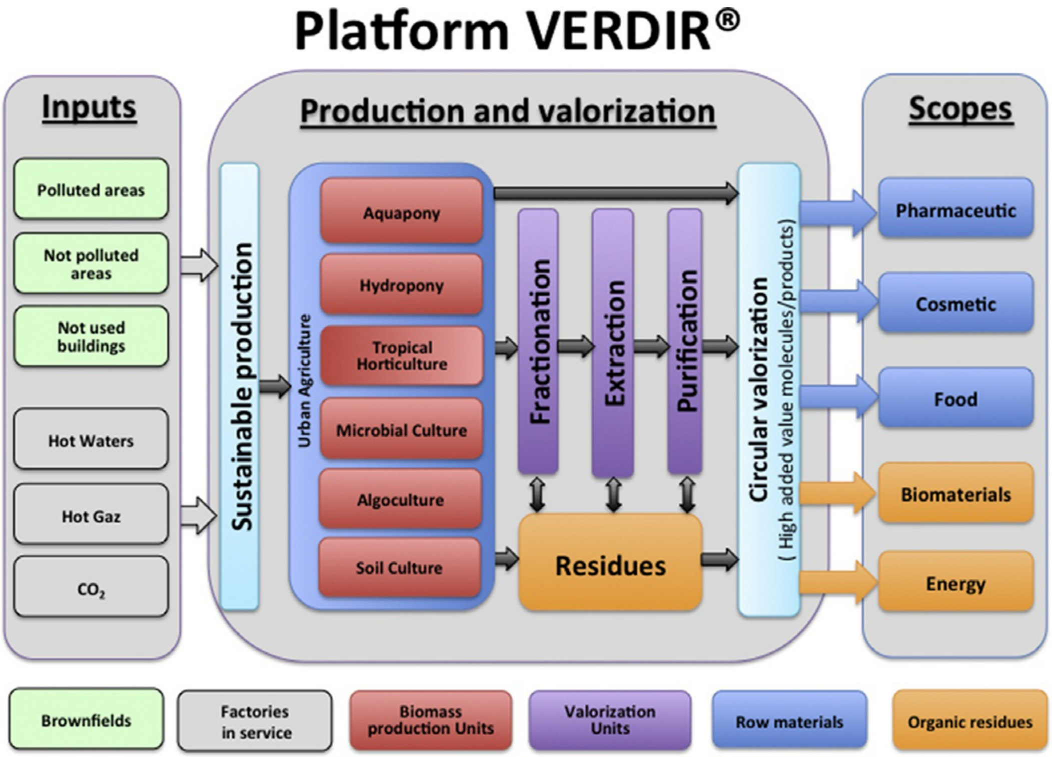
9.1.2 THE PROJECT

The main objective of VERDIR is the transformation of some industrial areas, steel in particular, into new "postcarbon" production areas by associating urban agriculture to it.

This conversion would result in:

- boosting the development of biomass to be used in the agro-food, pharmaceutical, and cosmetic sectors;
- the development of an innovative platform arranged around the optimization of the biomass of urban and peri-urban areas in different fields of applications. The main priority of this platform will be the optimization of high-value-added molecules;

The structure put in place by VERDIR will seek to value the expertise and multiple skills acquired through biomass material optimization technologies by adapting them to the principles of urban agriculture.



The platform will offer:

- Agro-food products grown in aquaponics, hydroponics, etc.;
- Processed products derived from the optimization of the biomass (high-value-added molecules such as artemisinin and camptothecin);
- Advisory activities for the implementation and integration of technologies developed for industrial customers;
- Additional services related to the acquired expertise: assistance in setting up R&D projects, technology and competition watch, training…
- Initially, the platform will be built on the strength of the project teams, but its scope of operation will expand subsequently through a continuous innovative dynamic to develop new applications with new partners.

9.1.3 OPPORTUNITIES

9.1.3.1 Current Challenges

1. *Pollutants are found even in organic cultivation*. The "bio" label requires the use of organic fertilizers and no chemical pesticides. Soils, however, are not always free from pollution

[1]. Plants are open to air pollution. Heavy metals are, thus, found even in plants grown using organic farming methods.

2. *Some crops come from far away*. Due to weather conditions, some species do not develop well or at all in our regions. In 2011, Belgium was the ninth food-importing country and, paradoxically, the ninth exporting country with an importing balance sheet that totalled $5 billion.
3. We are seeing a deterioration in the quality of fruits and vegetables and diversity is declining. This is the consequence of selecting varieties and the overuse of soil in order to maximize yield [2].
4. *Each crop has its life cycle … faster or slower*. It is impossible to farm everything and at any time because of the necessity to match the needs of the cultivated crops (light, temperature, etc.) to environmental conditions (sunshine, type of soil, etc.). Moreover, plant cycles are constantly disturbed by natural disasters, a possible consequence of climate change. That said, some years are considerably better than others in terms of yield.
5. *A steady decrease of croplands*. Thirty million hectares of croplands will chop off to build cities between 2000 and 2030 [3]. The selection of species, fertilizers, pesticides, and GMO even out of Europe contributes to improving yields in terms of quantity to the detriment of quality and diversity.

9.1.3.2 Future Challenges

1. There will be 9.8 billion mouths to feed in 2050 according to estimates.
2. Among them, 2.1 billion will be above 60 years with a growing demand for health and beauty products, compared to 962 billion today [4].
3. Furthermore, this population is increasingly residing in cities, resulting in more supply and quality problems due to challenges in the transport sector.

9.1.3.3 Opportunities in Europe

1. *Developed countries have industrial wastelands in abundance*. When companies shut down or relocate, they leave behind them several contaminated wastelands. These lands are unproductive until they are depolluted. There is, however, lack of financial resources to carry out the decontamination activities.
2. *And there are several disused buildings* in a pretty horrendous condition.
3. Industrial energy losses are estimated at 30%. Most often, companies in the industrial sector are located in the surroundings of wastelands and disused buildings. Most of these companies discharge energy in the form of gas or vapor. These could be collected for other uses.

9.1.3.4 Opportunity for Wallonia (Southern Belgium)

VERDIR provides an opportunity for all of Wallonia. In fact, the project will contribute to:

- Turn decommissioned assets into an opportunity (abandoned sites);
- Exploit the potential of lost energies (energy by-products);

- Promote a solid urban agricultural chain with international recognition;
- Develop the necessary technological tools for the development of an environmentally friendly production system and economically sustainable;
- Develop a platform that provides an international venue for partner companies to showcase their expertise for eventual exportation;
- Lastly, the project will produce, in a responsible manner, quality products of high added value.

The potential for urban agriculture is huge in Wallonia. In fact, Wallonia has more than 10,000 hectares of unused industrial wastelands that could be exploited through urban agriculture.

9.1.4 ACTIVITIES

The VERDIR initiative relies on several inputs offering several competitive benefits. The inputs that the project aims to maximize are:

Input I: Abandoned industrial buildings.

Input II: Abandoned industrial lands.

Input III: Recovered heat from the vicinity (energy by-products, incinerator, etc.).

These inputs are the building blocks on which activities are built. Input III is cross-cutting. It can fuel inputs I and II.

In every activity, several technologies are used to promote a technically and economically sustainable way of farming. The inputs, combined with good technologies (energy conversion tools, artificial light, artificial intelligence, etc.), must help create competitive benefits, both in qualitative and quantitative terms in comparison with traditional farming methods.

In practical terms, the VERDIR project is actually organized is three main phases, each connected to one or more inputs. Details of the different projects are provided in the following sections.

9.1.4.1 Tropical Plant Factory

The pharmaceutical sector is ready to switch to a greener economy. In fact, among the targeted sectors of the pharmaceutical industry, bio-based chemistry has a huge potential in terms of purchasing raw materials and the development of new high-value-added molecules. To foster a positive development of the sector in the future, special attention should be given to the type of biomass used; this will depend on the vegetable materials used, their yield per hectare, their availability, the processes and farming and enhancement technologies as well as the level of complexity accepted upstream (raw materials) and downstream (one or more products).

The use of biomass is a priority within the Tropical Plant Factory project. The fractionation, extraction, purification/identification of secondary metabolites derived from plants grown in warm regions as well as the optimization of residual biomass are closely interrelated. The development of an industrial sector producing pharmaceutical compounds or plant-based extracts through the identification of active phytochemical compounds and valuable biological activities cannot be separated from the extraction activity. This entails the development of the process from a laboratory scale to the study of its scale-up: the extraction process, directly integrated to the industry. With time, the development of a self-sustaining sector based on the circular economy as indicated in the Tropical Plant Factory project will inevitably require a global biomass optimization method. That implies a cracking/biorefining of the residual biomass after extraction into new by-products.

The first VERDIR project will, therefore, consist in creating and operating a Tropical Plant Factory. That will be a tropical hot greenhouse geared towards the production of plant biomass. This biomass is optimized mainly through extraction, cultivated plants, and high value-added molecules intended for the pharmaceutical and para-pharmaceutical sectors.

Within the circular economy sector, the distinctiveness and the innovation of this project stem from the complete control over the entire chain. It stretches from the growing of crops to molecules/finished products, as well from the ability to optimize industrial wastelands and/or energy by-products from companies.

Inputs II and III are the main optimized inputs in this phase, that is, abandoned industrial lands and recovered heat.

This option offers several competitive benefits:

- Ease of obtaining a building permit;
- Low cost of occupation;
- Proximity to urban areas (markets);
- Access to energy at a competitive price (25% saving compared to traditional supply channels thanks to inputs III);
- The possibility of granting subsidies.

A pilot program is set up. It aims at creating and exploiting a 9000 square surface on ACEC site at Herstal (Belgium).

9.1.4.2 Smart Plant Factory

The precise control over the growing conditions of crops dramatically scales performance and helps to meet the challenges of the 21st century: produce more and in better quality to feed and heal 9.8 billion people (by 2050) by reducing adverse impact on the environment.

With developments in lighting and automation, it is now possible to develop fully controlled closed systems to grow crops. These systems can also be optimized to foster local production of high-value-added molecules such as vincristine and vinblastine used in treating tumors.

To locally produce these precious molecules, it’s not just enough to create the conditions to grow crops locally. We must be able to produce them locally in huge quantity, standardize them (steady high quality), extract as many molecules as possible, and maximize the use of the residues. In other words, three elements must be considered for better use: the molecules content in the cultivated crops, the extraction, and optimization of the crop.

The second project of VERDIR is, therefore, the exploitation of refered containers to grow different types of crops. Input I is used for this activity, that is, abandoned industrial buildings.

The use of containers in growing crops offers several benefits:

- Control over all the factors that shape the environment of crops (humidity, heat, light, etc.);
- The possibility of multiplying the growing areas by stacking containers;
- Mobility.

The development of the Smart Plant Factory (SPF) is real innovation because artificial intelligence has been integrated into the project in order to link the phenotype of cultivated plants to the environmental conditions of the container.

An Intelligent Container offers a fully controlled environment. It is built in a fully equipped standard insulated container to grow crops hydroponically and in aeroponics:

- it offers control of temperature and humidity through HVAC,
- provides a management of internal modules in order to make better use of the available space,
- offers a system of artificial lamps to select the accurate intensity and wavelengths,
- provides a circulatory and injecting system to provide plants with nutrients,
- provides a CO_2 injecting system to accelerate growth,
- is managed via a monitoring/control software thanks to sensors and the control of all previous equipment,
- it is monitored remotely to effectively manage maintenance and ensure yields.

Machine learning techniques such as learning through reinforcement are implemented to manage the container. They take advantage of all the available measures as well analysis in the content (useful molecules) to identify how to best control the equipment while minimizing energy consumption. This technology that offers a hard to imitate competitive benefit shall be patented.

9.1.4.3 Ecosol

Inventories in Wallonia (SPW-DG04 and SPAQ*u*E) estimate the number of industrial wastelands to be 5000, representing a total surface area of 10,000 hectares. Of all the wastelands identified, it should be noted that there are 1500 “sites to be redeveloped” mostly nonpolluted and 3500 other sites considered to be contaminated. The Walloon Region has provided funds for the redevelopment of 72 hectares per year from 1995 to 2008. As per an estimate carried out in 2008, the redevelopment cost for the most polluted 2000 sites ranged from 2.5 to 5 billion euro.

Leaving these sites as industrial wastelands and soils with varying organic and/or metallic pollution profiles poses health, environmental, and economic problems. In fact, marginal wastelands actually have no economic or social value. In view of sustainable development and ecological transition, it is vital that, on the one hand, industrial wasteland should be integrated into the socioeconomic fabric of Wallonia, and on the hand, to further take into consideration environmental factors for the optimization of industrial wastelands.

At the same time, there exists a growing competition in attributing lands to different types of crops (production of food, metabolites, and biomass used as an energy source). These problems call for innovations geared toward diversifying crop-growing techniques on marginal soils.

The ever-increasing landscape deeply affected by industrial activities is a challenge to land use planning and the management of the environment. While these areas should quickly be given their economic value so as to restore their attractive potentials, they may sit for many years without decontamination and it may take a relatively long period (more than 5 years in some cases) between decontamination and their putting into use.

The ECOSOL project takes advantage of input II and the periods when the industrial wastelands are not in use (before, during, and after decontamination) in order to add value to these. In fact, these wastelands, generally not suitable for growing food crops, are, however, a veritable opportunity to grow high-value-added molecules for the pharmaceutical sector after adequate purification.

New crops suitable for marginal soils can, therefore, offer opportunities for technological redeployment in the region.

These wastelands form a particular ecosystem so much so that the implementation of their regeneration requires a deep knowledge of the functioning of biological systems found therein. Plant systems must adapt to contaminated and disturbed soils. These conditions present additional selection pressures on their populations, imposing coping skills that are important to find out.

The specific objectives of this project are:

- The inventory of useful crops and the selection of candidate species.
- Soil characterization before and after decontamination on the basis of their potentials.
- The selection of crops with high optimization potentials on industrial wasteland.
- On-site farming and agronomic study of the land on the basis of decontamination modalities.

9.1.5 CONCLUSION

The protection of our environment and that of the human well-being (food and health) are major stakes for the future generations which we have to take care of and solve now.

Therefore, we have to innovate to change our methods of production and our vision of the “Products” and of the “Wastes.”

We have to add the notion of “Environment” and “Social” in the economic models of tomorrow as well as of today. We have to accept that the future crop production systems can combine both “Traditions” and “Technologies” as long as they contribute to the preservation and improvement of our environment and well-being.

It is precisely in that perspective that the institutional project of the University of Liège, VERDIR, was developed. It contributes to change threats (industrial waste, polluted soil, unavoidable energy, etc.) into opportunities to create economic, environmental, and social value (medicines, quality food, etc.) through innovating and collaborative models.

The project is rapidly developing and, while other activities such as Tropical Plant Factory, Smartbox and Ecosol are ongoing, other projects are coming.

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CHAPTER

9.2

Aquaponics in Plant Factory

Masato Endo

Department of Marine Biosciences, Tokyo University of Marine Science and Technology, Tokyo, Japan

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9.2.1 INTRODUCTION

Global aquaculture production is growing rapidly, and it is getting close to the capture fisheries production in recent year [1]. The aquaculture with feeding to aquatic organisms, e.g., fin fish, crustaceans, etc., has been mainly carried out in natural water environment, i.e., net cage, and net pen, or to use natural water introduced to ponds and tanks. Waste materials

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discharged from aquatic animals in aquaculture are almost loaded directly to natural environment and they often cause water pollution.

On the other hand, recirculating aquaculture system is driven with several kinds of devices for water treatment and the rearing water can be reused when waste materials are accumulated until the limit to maintain animal health [2–5]. The aquaculture system can accumulate waste materials, while effective method for totally removing waste materials does not exist except nourishment absorption by plants. Therefore, in order to prevent the water pollution caused by aquaculture, recirculating aquaculture system combined with hydroponics, called "aquaponics," was developed about 40 years ago [6–8].

From the point of view of food production facility, recirculating aquaculture system has characteristics similar to plant factory, for example, it can (1) be easily constructed in wide area, i.e., arid regions, polar regions, etc. compared with other aquaculture systems, (2) control the production environment including water, light, and feeding condition, and (3) protect products from parasites, toxic substances, bacterial, and viral diseases [9,10]. Plant factory using artificial light has potential to remove waste substances from rearing water in recirculating aquaculture system; in other words, the factory can evolve to combined agricultural and fisheries production, i.e., "aquaponics factory."

This section explains the method of water management, material flow control in aquaponics including consideration of characteristics of plant factory with artificial light, and newly aquaponics productions with saline water.

9.2.2 AQUAPONICS

Aquaponics is the food production system with material recycling that combined recirculating aquaculture system with hydroponic system. Fish are mainly fed commercial diet and the excreted materials from fish are accumulated in rearing water and directly used by hydroponics plants as a liquid fertilizer [6–8] (Fig. 9.2.1). Tilapia and lettuce, tomato, basil, etc. in United States, [11–13], and also Murray cod and various leaf vegetables, garden plants such as Swiss chard in Australia, have been used for aquaponics production so far. Besides these, several species of food and ornamental freshwater fish that can be raised in freshwater condition have been used for aquaponic production.

Aquaponics was originally developed for water recycling in aquaculture system, while, in recent years, several American hydroponic companies that manage hydroponics system with solar light and auxiliary artificial light have introduced waste water discharged from fish in recirculating aquaculture system as the organic fertilizer and they succeeded vegetable production and sold them as leading products [14].

The recirculating aquaculture system consists of rearing tank, several kinds of water treatment system, i.e., settling tank and biofilter, water temperature control device, and aeration system (Fig. 9.2.2). In particular, biofilter works for detoxifying ammonia excreted from reared aquatic animals to low-toxicity nitrate ion by the effect of bacterial nitrification [9].

On the other hand, there are several types of culture method in hydroponic system.

Deep water culture (DWC) system in which raft grow beds are flouted on the hydroponics tabs, nutrient film technique (NFT) system in which plants are transplanted and a small amount of liquid fertilizer flows in the grow channels or pipes, and gravel bed (GB) system

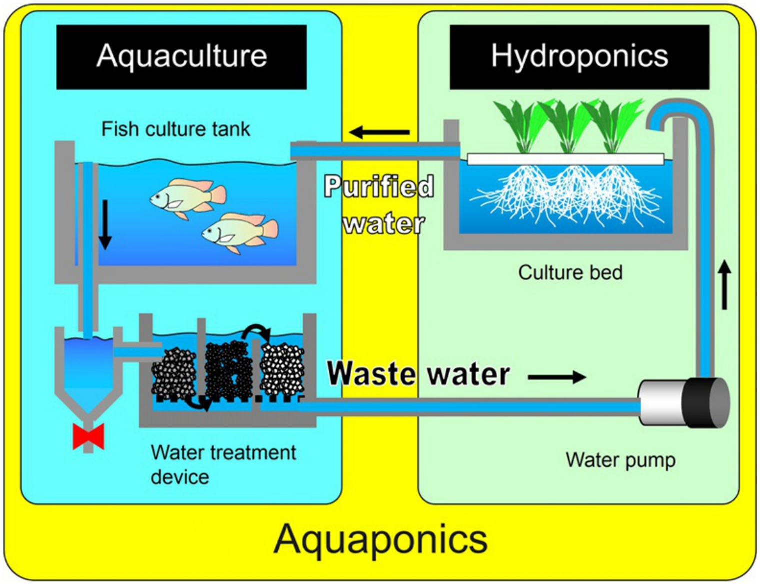

FIG. 9.2.1 Schematic diagram of combined recirculating aquaculture and hydroponic systems, aquaponics.

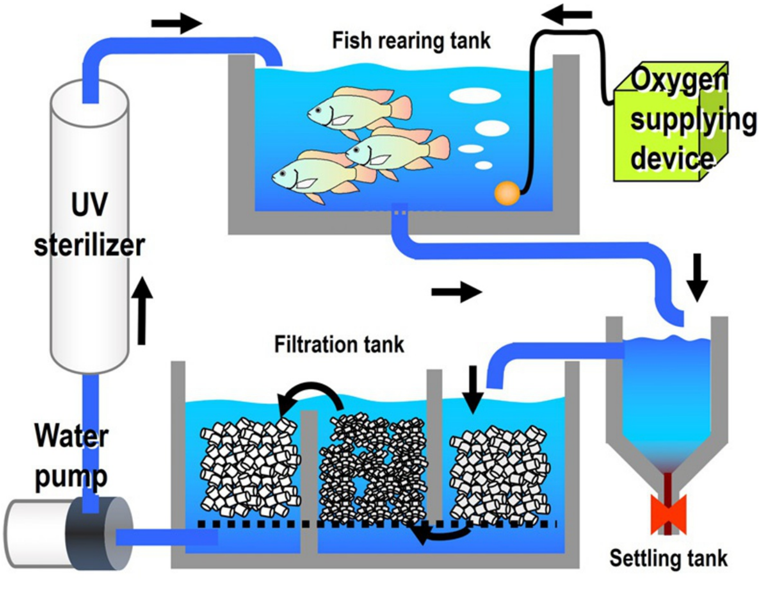

FIG. 9.2.2 Schematic diagram of recirculating aquaculture system with tilapia.

in which gravels are laid in cultivation tabs equipped with an intermittent water supply system called “bell syphon” have been used in hydroponics system (Fig. 9.2.3). Each hydroponics system has different characteristics, the components of fertilizer and temperature are stabilized because relatively large amount of fertilizer is used, and oxygen supply is essential

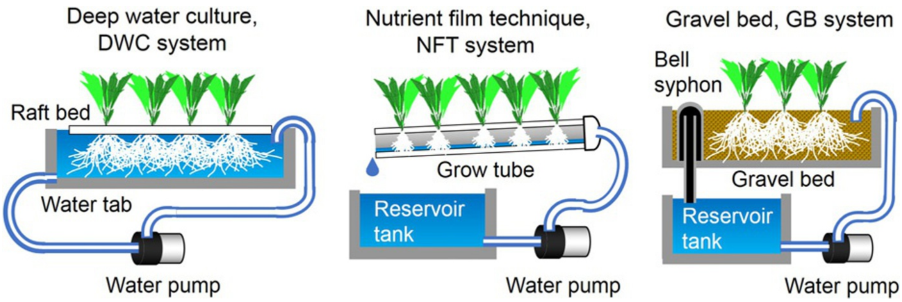

FIG. 9.2.3 Schematic diagram of three types of cultivation systems for hydroponics.

in DWC system, the amount of used fertilizer is small and the composition and temperature are relatively unsterilized, while oxygen supply isn't needed because the greater part of root is exposed to air in NFT system, and the gravel beds can play the role of biofilter of recirculating aquaculture system in GB system [15]. Hydroponics system with various light conditions, i.e., solar light, solar light with supporting artificial light, and completely artificial light, is available for aquaponics.

9.2.3 WATER MANAGEMENT

9.2.3.1 Management of pH and Electric Conductivity

The rearing water for farmed fish in aquaculture system is used as liquid fertilizer and it is circulated between aquaculture and hydroponics system in aquaponics; the water management is greatly limited compared with solo recirculating aquaculture system or hydroponic system. Table 9.2.1 shows the differences of water management of the three systems. In terms of pH management, the pH of liquid fertilizer is set to 5.8–6.5, relatively acidic condition that is similar to soil environment of plant cultivation in hydroponic system [16]. However, rearing water of that is adjusted to 6.5–8.0, relatively from natural to weakly alkaline condition that is optimum pH condition on fish growth [17] in aquaculture system. Therefore, the pH of water in aquaponics system is controlled to 7.0 that is intermediated value between two other systems [18]. The concentrations of liquid fertilizers have been alimented by reading of the electric conductivity (EC). The EC is 0.8–2.3 mS/cm and it depended on components of fertilizer and the components vary as to the species of cultivated plants. The components of rearing water in fish culture are changed by the condition of accumulated substances. The materials excreted from reared fish are oxidized and decomposed by chemical reactions and effect of bacterial activity under aerobic environment. Ammonia having high toxicity excreted from the fish is oxidized to nitrate via nitrite by the activity of nitrifying bacteria fixed to filter materials. Solid waste is removed from settling tank of aquaculture system and processed with a proper method. Utilization and application of rearing water is one of the important matters in aquaponics. The ratio of substances in the rearing water and solid water depends on dissolution equilibrium and each substance has deferent dissolution limit in water. In cases of water management of hydroponics, lowering of the pH of liquid fertilizer

TABLE 9.2.1 Comparison of Water Management of Recirculating Aquaculture, Hydroponic System, and Aquaponics

	Recirculating Aquaculture System	Hydroponic System	Aquaponics
pH control	6.5–7.0	5.8–6.5	7.0
EC (mS/cm)	0.0–3.5 as fresh water	0.8–2.3	0.3–0.5
Nutrients and wastes	A part of waste discharged from reared fish is accumulated to the rearing water.	Inorganic fertilizer	Waste materials discharged from aquaculture system + Shortage elements
Water management	Periodically water exchange	Adding fertilizer at the beginning of cultivation and adjustment of fertilizer concentration by EC monitoring	Consideration of the mass variance of products based on material flow and Control of feeding amount of fish (60 g feeding/m^2cultivation area)

provides that low solubility substances such as phosphorus and trace elements can be easily solved in the fertilizer. Precipitation of nutrients is easy to occur in aquaponics, because the water pH should be adjusted to relative high, pH of 6.5–7.0. Accordingly, substance in the water is totally suppressed and the EC is adjusted to 0.3–0.5 mS/cm with controlling productions of fish and plant.

9.2.3.2 Addition of Shortage Elements

The contents of waste materials from recirculating aquaculture system cannot cover all nutritional elements for growth of hydroponic plants. The idea to identify shortage elements is comparison between elemental contents of waste materials discharged from aquaculture system and cultivated hydroponically plant. Fig. 9.2.4 shows comparison between the elemental contents in lettuce [19] and aquacultural wastes from tilapia reared in recirculating aquaculture system [20,21] based on the nitrogen content in lettuce and total nitrogen in rearing water. Phosphorus, calcium, and trace elements in the aquacultural wastes were enough to cultivate lettuce in the case of solid waste utilization, while potassium and manganese were deficient even if both rearing water and solid waste were used as the fertilizer and the necessity of adding them from the outside was suggested. In general, the solid waste is removed from aquaculture system and discarded after appropriately processing and shortage nutrients that are not concluded in the rearing water are added from outside. However, it is certain that most of essential trace elements for plant cultivation are contained in the solid waste.

The investigation to use the elements in the solid waste was carried out for one of the methods to create liquid fertilizer. Solubilization rates of nitrogen, phosphorus, calcium, magnesium, sodium, potassium, iron, zinc, manganese, and copper were determined after digestion of solid wastes with hydrogen peroxide and sulfuric acid by microwave heating in closed Teflon vessels. As shown in Fig. 9.2.5, the digestions with 0.1, 1.0, and 10.0 mmol/g solid

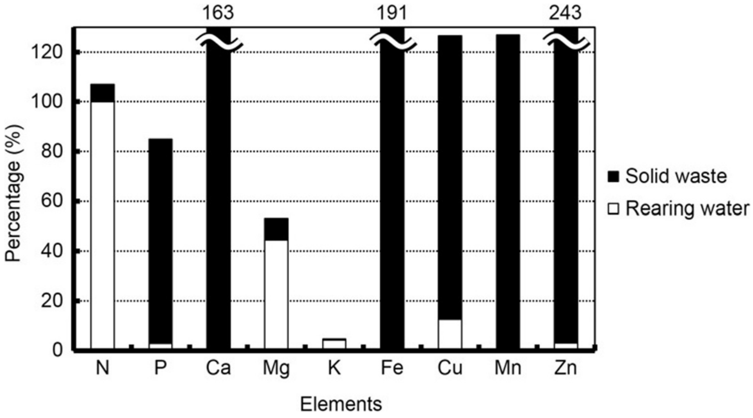

FIG. 9.2.4 Comparison between the elemental contents in lettuce and aquacultural wastes from tilapia reared in recirculating aquaculture system based on the nitrogen content in lettuce and total nitrogen in rearing water.

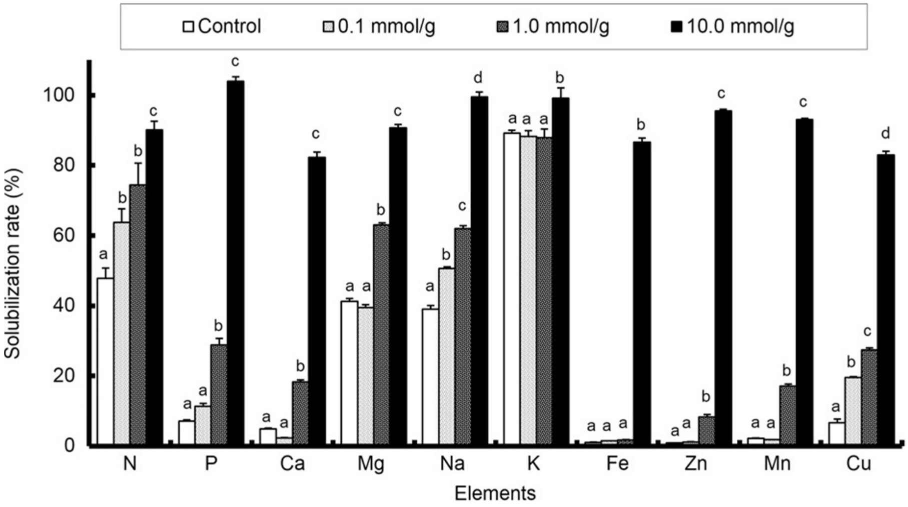

FIG. 9.2.5 Solubilization rate of elements in the solid wastes digested by microwave heating in closed Teflon vessels with 0.1, 1.0, and 10.0 mmol/g solid waste of sulfuric acid after the processing with 40 mmol/g solid waste of hydrogen peroxide. These values are represented mean ± S.D. ($n = 3$). Different alphabetical letter above the bars indicates significant difference among the treatments (Tukey's HSD test, $P < 0.01$).

waste of sulfuric acid at 175°C were conducted after digestion with 40 mmol/g solid waste in hydrogen peroxide at 125°C. In the digestion with 10 mmol/g solid waste of sulfuric acid, more than 80% of quantum in all the elements dissolved out from the waste, while the digestions with lower concentrations of sulfuric acid was not effective. The result indicates that addition of more than 40 mmol/g solid waste of hydrogen peroxide and 10 mmol/g solid waste of sulfuric acid was efficacious for the solubilization of solid waste [22].

The addition of potassium and manganese sources from outside in the rearing water can result in an effective pH control. Nitrification process induces to lower pH of water with nitrate production from excreted ammonia in recirculating aquaculture system. Sodium bicarbonate or coral sand composed mainly of calcium carbonate are always used to prevent pH decreasing. Addition of potassium hydroxide and magnesium hydroxide for this pH control can provide both pH rising and enrichment of potassium and manganese to the rearing water for aquaponics water management.

9.2.3.3 Utilization of Chemical Equilibrium Software for Water Management

The water management of aquaponics is complicative because both supply and consume of substances in the water occur continuously and simultaneously. Understanding of chemical dissolution equilibrium is needed for the grasp of existences of each element in the culture water. As a first step of this, we attempted to compare chemical dissolution equilibrium for aquacultural waste between the actual and estimated data. In order to evaluate the kinetic behavior of elements discharged from tilapia in a recirculating aquaculture system, a chemical equilibrium speciation model, Visual MINTEQ [23], was applied to elemental composition data from tilapia waste. Data from a 189-day rearing period using recirculating aquaculture system grown-tilapia and some supplemental data were used to confirm the kinetic behavior, i.e., dissolution/precipitation behavior. As shown in Fig. 9.2.6, similar kinetic behavior was obtained from under the condition of pH 7.5 and adding 3.91 mmol/L of carbonate as the expected leaching substance from coral sand [24]. The chemical equilibrium speciation model used for this study covered only the data of inorganic materials. The aquacultural waste includes organic matter, but this result suggests that approximate dissolution/precipitation equilibrium on the aquacultural waste can be estimated.

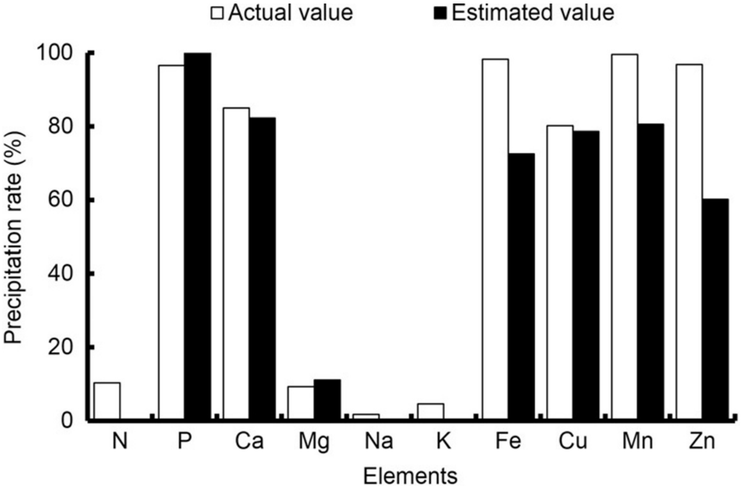

FIG. 9.2.6 Comparison of chemical precipitation equilibrium for elements in aquacultural waste between the actual and data estimated by a chemical equilibrium speciation model.

In the future, the mathematical modeling of both fish and plant production including dissolution/precipitation behavior will be effective for estimation of material flow and productivity in aquaponics.

9.2.4 CONTROL OF MATERIAL FLOW

9.2.4.1 Stabilization of Material Flow by the Production With Multigeneration

Material flow in aquaponics is indicated as the combination of aquacultural waste discharge from aquatic animals, assimilation of nutrients by hydroponic plants, and their processes. The production planning of complete artificial food productions, i.e., indoor land-based aquaculture with recirculating aquaculture system and plant factory using artificial light, is more stable than that of other types of aquaculture and agriculture because the production facilities can control their environments and they are less subject to natural environment. However, the aquaculture and hydroponic productions are quite different as per their production cycle. The fish production from fish introduced to harvesting requires from half year to 2 years, while that of plant production needs from 1 month to several months, generally. As one of the methods to stabilize the material flow, the production with multigeneration has been used in aquaponics production.

For instances, lettuce production by using hydroponic system needs from 4 to 6 weeks for one production cycle. The range of the dry mass in 5-week production of lettuce between one production cycle, i.e., 5-week production and the production with five generations that germination and harvest are conducted every week. The basic data of dry mass were obtained from Both et al.[25]. The result suggested that the range of dry mass can be reduced to 1/9.6 by changing production plan. The gain of dry mass can be thought of as the amount of nutrient absorption from the water and this result shows to strongly suppress the variation of nutrient absorption in lettuce production. In the consideration of fish culture with multigeneration, the comparison of tilapia that is candidate species for aquaponics production was carried out. The basic data of tilapia production were used from Endo et al.[20]. The result indicated that the range of weight gain of tilapia can be reduced to 1/4.5 by changing production plan from one cycle production to six generation production that introduction and harvest are conducted every month in 6-month fish production. Fish reproduction has seasonality and it depends on the fish species. This type of operation is limited to use as the fish species can reproduce year around with a technique in propagation control.

9.2.4.2 Split Water Operation of Aquaculture and Hydroponic Systems

Plant factory using artificial light has characteristics of high independency and cleanliness, and sanitary culture of plants has been generally conducted to avoid insect damage, bacterial, and viral diseases in the facility. And also, commercial production of recirculating aquaculture system has been operated inside of the facility to prevent from parasites, bacteria, and virus infections; however, the aquaculture system has biofilter with various bacteria for water purification and no small number of enterobacteria from fish exist in the system. In cases of aquaponics, detailed techniques that harmful bacteria are excluded and useful bacteria are

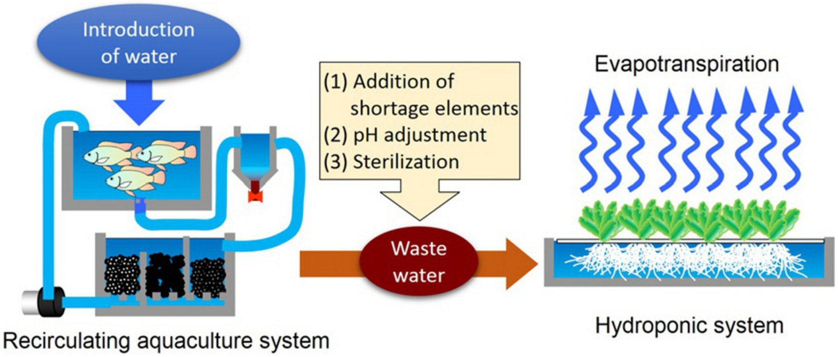

FIG. 9.2.7 Material flow of split water operation of aquaculture and hydroponic systems.

increased selectively are needed for the bacterial control, because the water is shared between aquaculture and hydroponic systems.

Hence, split water operation of aquaculture and hydroponic systems is recommended as one of the solution to maintain the cleanliness of plant factory. Fig. 9.2.7 shows the material flow of split water operation of aquaculture and hydroponic systems. This method is that both recirculating aquaculture system and plant factory is operated separately, and the water is transferred from aquaculture system to hydroponic system. This idea is based on RASponics that the waste water in recirculating aquaculture system is used for hydroponic fertilizer, and new water is introduced to the aquaculture system and hydroponic system consumes the water by the action of plant evapotranspiration advocated by Timmons et al.[26]. The merits of this method are (1) concentration of waste water and shortage elements can be adjusted as hydroponic fertilizer, (2) the water pH can be lowered to hydroponic use and solubility of substances in the water can be raised up, and (3) sanitation management level of the water can be controlled by sterilization device or the like, for plant factory.

The methods of material flow in combined food production system should be considered based on the characteristics, conditions, and restrictions of each system, same as economic efficiency.

9.2.5 AQUAPONICS WITH SALINE WATER AND ARTIFICIAL LIGHT

9.2.5.1 Trail of Aquaponics With Salt-Tolerant Plant, Ice Plant, and Marine Fish, Kelp Grouper

Aquaponics have been mainly investigated and conducted commercially using fresh water and adaptive organisms [27]. However, there are few scientific reports on aquaponics that can be applied to marine fish production with recirculating fish culture system, and waste loading from the fish production becomes a serious problem.

In order to determine the optimum salinity level, the fish and plant ratio on aquaponics system with kelp grouper *Epinephelus bruneus* and ice plant *Mesembryanthemum crystallinum*, 28-day experiment was conducted by using aquaponics system consisting a 200 L-recirculating

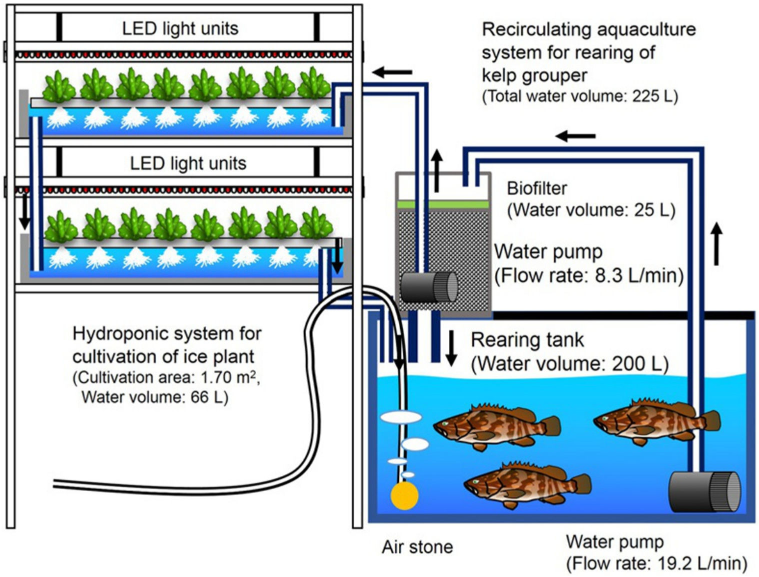
LED light units
LED light units
Recirculating aquaculture system for rearing of kelp grouper
(Total water volume: 225 L)
Biofilter
(Water volume: 25 L)
Water pump
(Flow rate: 8.3 L/min)
Hydroponic system for cultivation of ice plant
(Cultivation area: 1.70 m², Water volume: 66 L)
Rearing tank
(Water volume: 200 L)
Air stone
Water pump
(Flow rate: 19.2 L/min)

FIG. 9.2.8 Schematic diagram of the experimental system for aquaponics with kelp grouper and ice plant.

fish culture system and two hydroponics floating raft beds that have total cultivation area of 1.73 m^2 and total water volume of 66 L with LED illuminations. Fig. 9.2.8 shows the schematic diagram of experimental system. Four experimental systems were prepared for creation of deferent conditions, i.e., combination of two salinity levels (8 and 16 psu) and two stocking amounts of fish (1.0 and 1.5 kg/total body weight/system). Fish were acclimated to each salinity during more than a month and 23-day-old seedlings of ice plant were prepared for the experiment. The experiment was started using three to four fish of kelp grouper and 36 seedlings of ice plant per system. The fish were fed commercial feeds at the rate of 1% body weight/day and the plant were irradiated with more than 150 μmol/m^2 s of light and water temperature was maintained at 23°C during experimental period. The specific growth rate, SGR of kelp grouper, was around 0.7%/day in all the treatments and no significant difference was noted among the treatment. The SGR of ice plant in treatments of 8 psu–1.0 kg, 8 psu–1.5 kg, 16 psu–1.0 kg, and 16 psu–1.5 kg were 12.6%, 13.0%, 11.7%, and 11.6%, respectively. The SGR of 8 psu treatments were higher than that of 16psu treatment; however, there are no significant differences among the treatments (Fig. 9.2.9). Concentration of nitrate nitrogen in the culture water of the 8 psu–1.5 kg treatment was stationary and stable during experimental period, while the increment of nitrate concentration was observed in other treatments and the largest increments were occurred in the treatment of 16 psu–1.5 kg, followed by 8 psu–1.5 kg and 16 psu–1.0 kg in this order.

The results indicated that aquaponics with kelp grouper—ice plant can be established; 8 psu salinity is recommended for ice plant cultivation with waste water discharged from kelp grouper culture under the proper acclimation and 1.0 kg-total weight of kelp grouper fed commercial diets at the rate of 1% body weight/day is suitable for cultivation of 36 ice plant seedlings.

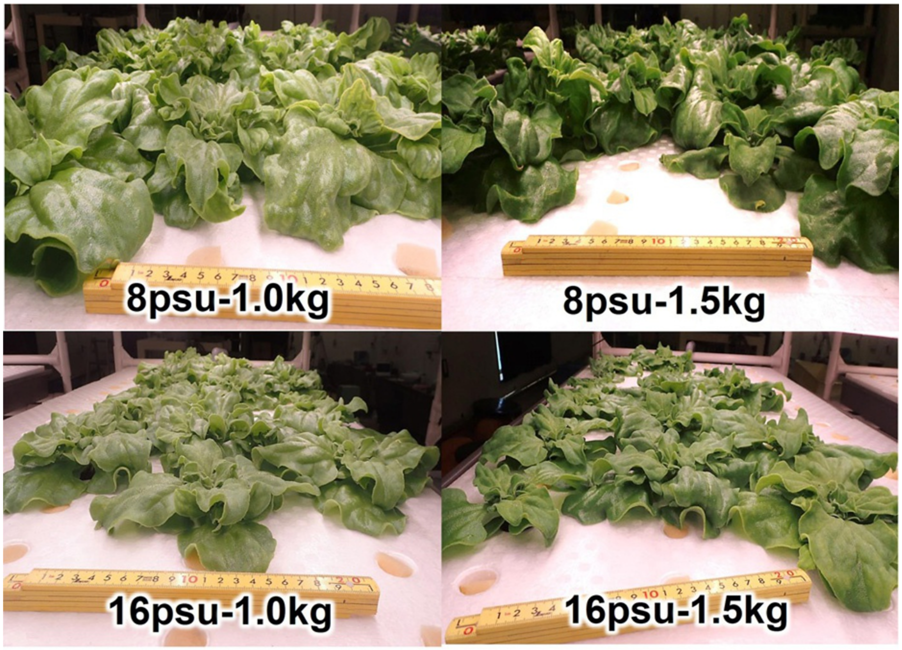

FIG. 9.2.9 Ice plants cultivated with rearing water of kelp grouper in aquaponic system using artificial light at the end of experiment.

9.2.5.2 Trail of Production of Sea Weed, Sea Grape Using Waste Water of Kelp Grouper

Cultivation trial of sea grape *Caulerpa lentillifera* was conducted by using waste water, elements contained waste water, solid waste, foam waste in recirculating aquaculture system with kelp grouper, and sea grapes were analyzed to estimate the availability of cultivations of sea grape and simulate the ability of absorbing elements in the waste water [28]. Culture of sea grape was conducted in 50 L tanks for 28 days with waste from kelp grouper or synthetic medium (Provasoli-Enriched Seawater, PES). Water temperature and pH were maintained at 28°C, and 8.0 or higher, respectively. In addition, salinities were set at 32 psu to confirm the tolerance of salinity, and photoperiod was controlled at 12 h light: 12 h dark in the all treatments. Figs. 9.2.10 and 9.2.11 show the schematic diagram of experimental system and the situation of sea grape culture, respectively. Sea grape cultured with waste water showed the highest specific growth rate that is 7.16, similar to that of sea grape cultured with synthetic medium. The results of elemental composition analysis by using inductively coupled plasma atomic emission spectroscopy and total nitrogen analyzer showed that the elements contained in the kelp grouper waste, i.e., waste water, solid waste, and foam waste are enough to grow sea grape except manganese, copper, and boron. Thus, these elements are needed to add from outside to culturing water and their quantities are 189.8, 99.4, and 157.5 μg respectively, on 1 L basis.

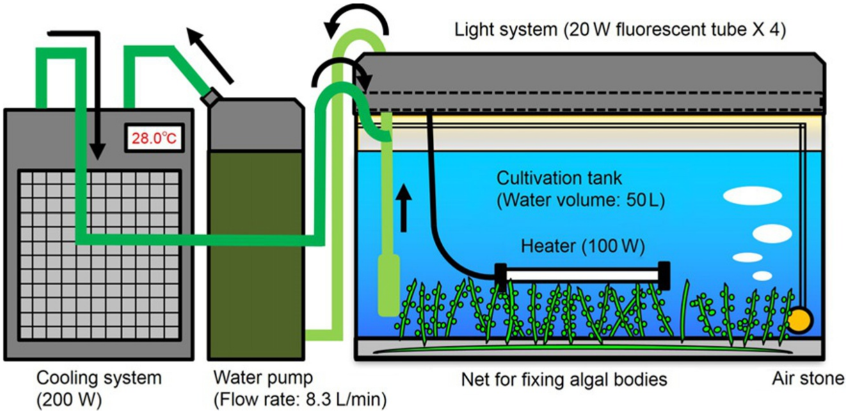

FIG. 9.2.10 Schematic diagram of the experimental system for cultivation of sea grape with waste materials discharged from kelp grouper.

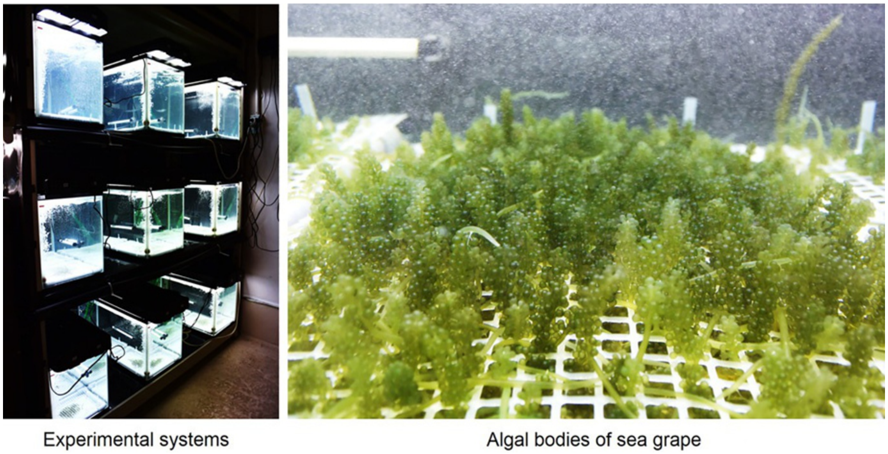

FIG. 9.2.11 Experimental systems and algal bodies of sea grape cultivated with waste materials discharged from kelp grouper using artificial light.

This trial leads seaweed culture in plant factory with artificial light and aquacultural waste. The optimization of culture condition for rising productivity, consideration of food safety by bacterial control, scale up, and profitability will be needed for the commercial production.

9.2.6 CONCLUSIONS

Effective water utilization is being looked for grovel food production. In aquaculture, there has been serious problem that is waste lording to natural environment for a long time. Land-based facility for food production, especially combined food production systems with material recycling, has a potential to reduce the amount of various consumed natural resources and wastes. Present aquaponics is just one of the methods of combined food productions and the establishment of various operating methods that are suitable for each purpose or object is desired for sustainable food production toward the future.

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CHAPTER

9.3

Advanced Technologies for Large-Scale Plant Factories—Integration of Industrial and Systems Engineering Approach in Controlled Environment Crop Production

Chieri Kubota[*], *Chao Meng*[†], *Sara Masoud*[‡], *Young-Jun Son*[‡], *Russell Tronstad*[‡]

[*]The Ohio State University, Columbus, OH, United States [†]Valdosta State University, Valdosta, GA, United States [‡]The University of Arizona, Tucson, AZ, United States

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9.3.1 INTRODUCTION

Plant factory using sole source electric lighting has been recognized as a unique production facility that is rapidly developing worldwide. The production capacity and facilities vary from a reach-in growth chamber for small-scaled applications such as residential kitchen or restaurant use to large-scaled warehouse applications with annual production capacity for several million high-value crop items. Currently, the largest production facility in North America is AeroFarms, located in Newark, NJ, with an annual production capacity of ~1000 tons of leafy greens. The types of crops grown in plant factories are leafy greens (e.g., lettuce and basil), medicinal plants (e.g., cannabis), small fruit (e.g., berries), and high-value transplants (e.g., grafted vegetable seedlings). Among them, commercial production of grafted vegetable seedlings in plant factories has been successfully introduced in Japan and the US, beginning in early 2000s [1,2]. Vegetable grafting has been widely used to mitigate the impact of soil-borne diseases, to enhance yields, as well as to increase tolerance against environmental stresses (e.g., low temperature) since the first application for intensive watermelon cultivations in the 1920s [3]. Growing grafted vegetable seedlings requires precise management of production schedules as well as controlled environments, which justify the use of plant factory.

While automation has been perceived as a crucial technological advancement needed to support this newly emerging controlled environment industry, feasible technologies with affordable costs and liability still need to be developed. As a consequence of slow R&D progress in automation, much of the critical work/tasks at plant factories are still mostly performed manually. Plant factories are generally considered as scalable systems for the "hardware" of the buildings, production systems such as multitiered shelving units, and lighting systems. However, software to effectively operate the hardware should be developed to optimize labor and other resources to maximize productivity and profitability. Use of a fully controlled environment with sole source electric lighting can make production more consistent and predictable; yet such facilities still require experienced production managers (or "Growers") who understand horticultural crop production as well as environmental control engineering. The success of plant factories is largely dependent on the skill set of these skillful growers even in fully controlled climate conditions. Sensors, automation, and information/data technologies can assist growers, but their costs are still prohibitive, especially when their performance is affected by many factors including "uncertainty." Biological systems (e.g., seeds, crops, pathogens, pests, and human workers) are typically the source of uncertainty and, therefore, make production management extremely challenging. Crop production involves various growth stages, environmental conditions, and biological genotypic differences (e.g., plant species and cultivars) responding to varied environmental conditions. These variables create a largely complex biological system that growers need to deal with on a day-to-day basis.

This chapter summarizes our transdisciplinary efforts to optimize production planning, labor management, new technologies (including automation), and resource allocations of large plant production facilities, considering the nature of highly unpredictable biological systems while highlighting study results from vegetable grafting nursery operations.

9.3.2 LOGISTICS OPTIMIZATION—APPLICATIONS OF INDUSTRIAL AND SYSTEMS ENGINEERING

In the field of factory automation, logistics optimization is a critical process for decision support prior to and during each operation. Discrete event simulation has become one of the most used analytical tools for large-scale, dynamic systems (e.g., manufacturing systems and supply chain). Advantages of discrete event simulation include: (1) it can take randomness over time into account, (2) it can address aggregate as well as very detailed models, and (3) it enables answering what-if questions in experimentations that are not easily possible in real systems [4]. Applications of such simulations have been reported, such as evaluating new technologies for a logistics transportation facility [5], health information system [6], urban highway reconstruction [7], and human cognitive workloads [8]. However, those in agricultural and horticultural crop production seem to be limited, presumably due to the complexity of biological systems that need transdisciplinary understanding.

9.3.2.1 Process Design and Cost Analyses

In applications for vegetable grafting, we developed a “framework” of independently simulating operations and input (Fig. 9.3.1) in various production stages of transplant production to find individual processing time, costs associated with each step of production, as well as possible bottlenecks [9,10]. Typically, vegetable grafting involves pregrafting and postgrafting stages and two plants (scion and rootstock plants) are grown separately in pregrafting stages to join together one grafted plant through grafting, healing, and growing-out/finishing stages. Production requirements (e.g., environmental conditions, time from seed to graft, fertilization, planting density) are species- or cultivar-specific. For many cases, scion and rootstock plants require different amount of time to reach the graftable growth stage. Simulation results can help growers or production managers make necessary decisions in order to design and optimize the production operation.

Meng et al. [9] demonstrated the use of such a framework to evaluate various methods and capacities of grafting operations under different scenarios (e.g., electricity rate, wage rate, machine price, and risk of disease). Fig. 9.3.2. demonstrates how the simulated relative cost of production, “grafting throughput time”, and capital expense to complete a given number of grafts vary [9]. The grafting throughput time is defined as the time duration for which an order of selected number of plants stays in the grafting operation. Among three grafting capacities examined, the fastest operation was achieved by having both manual grafting (15 workers) and automated grafting (using 15 machines), and the slowest by having only 30 grafting workers. This is not surprising as machines have higher grafting capacity than human workers. Of interest, adding three more machines while eliminating all grafting workers achieved an intermediate level of processing time and successfully reduced the production costs to a similar level of mixed use of manual and automation. This type of analysis can be used to determine an efficient number of workers and machines to meet the production criteria selected.

9.3.2.2 Task Allocation and Labor Management

Grafting nurseries provide plants to greenhouse and open-field crop producers. The seasonal nature of vegetable crop production also makes grafting operations very seasonal,

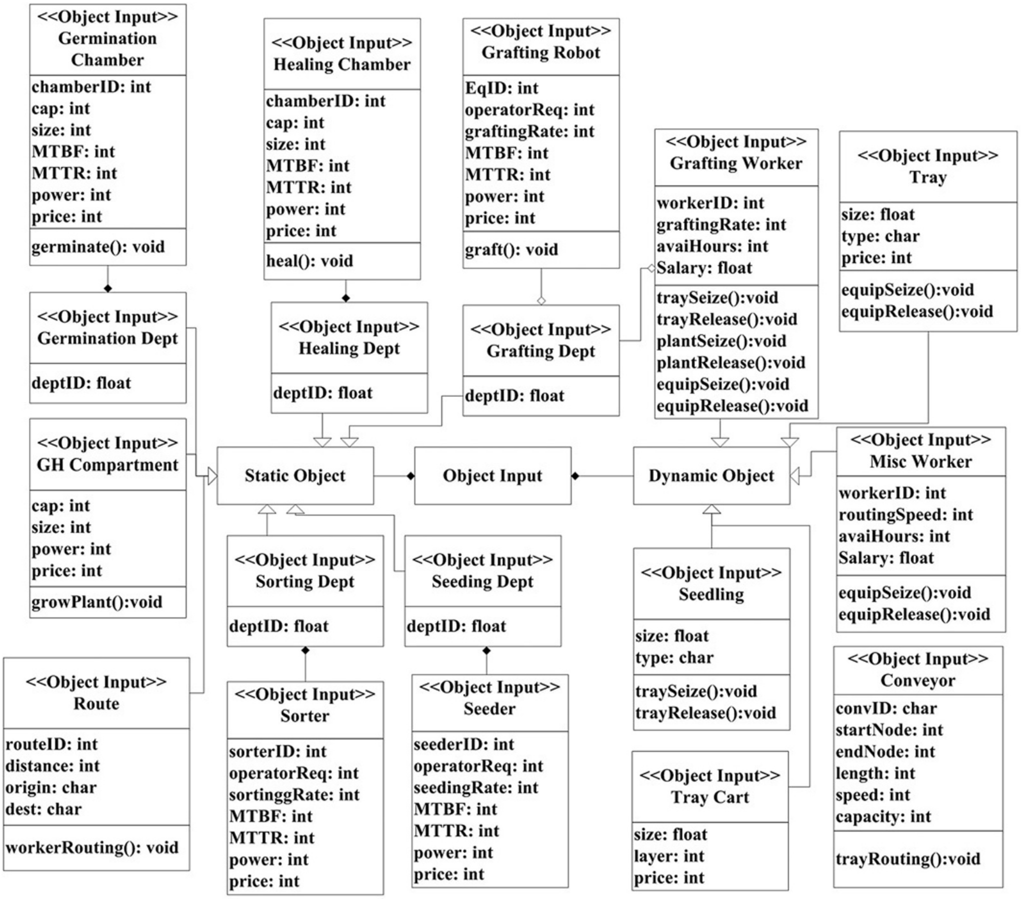

FIG. 9.3.1 Object input classes used in the framework of simulating vegetable grafting operation [10].

regardless of the plant production system used (i.e., traditional greenhouse vs. indoor plant factory). When grafting is performed manually, typically the grafting operation has to employ temporary workers to meet a labor need which is significantly larger during peak seasons. Grafting managers configure a suitable grafting workflow design as well as allocation of tasks among workers with various levels of grafting experience, which is a critical aspect of effective production management for grafting nurseries. The selected workflow design and how workers are assigned to different tasks greatly impact the resulting performance of the grafting operation. Optimization based on simulation likely improves efficiency and reduces per unit production costs. Fig. 9.3.3 shows a typical process to find an optimized solution for a given "what-if" scenario.

In our preliminary study [11], two workflow designs were selected to compare the expected daily number of grafts using a predetermined number of workers and their experience levels (low, intermediate, and high) for each grafting process task. The first workflow design examined was cellular manufacturing, which is also known as "one-person

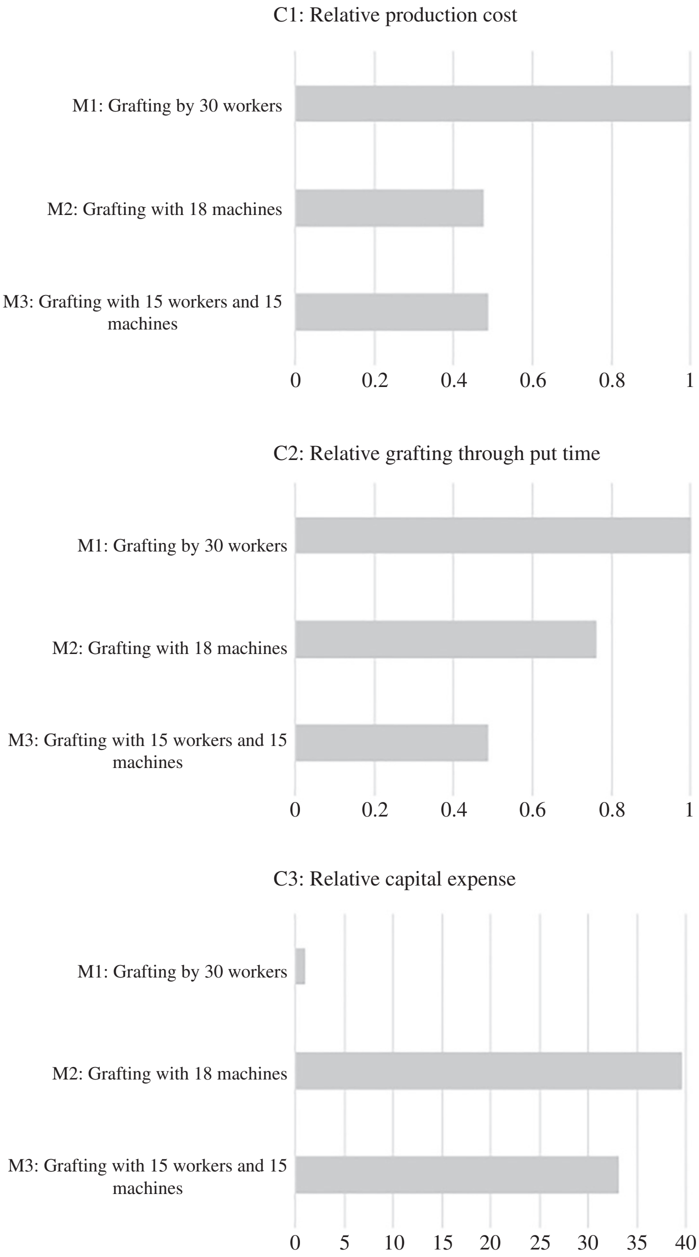

FIG. 9.3.2 Relative production costs, throughput time, and capital expense simulated for three selected grafting capacities (M1-3). The values are shown relative to the manual grafting with 30 workers (M1). *Adapted from Meng, C., et al., Comput. Electron. Agric. 102 (2014) 73–84.*

assembly." In this workflow, each worker performs every step/task of the grafting process (e.g., cutting scion and rootstock plants, placing grafting clips, and joining two plants). The second workflow design was an assembly line or "line operation" where each worker performs one task assigned based on their skill level. For a commercial manager who provided necessary personnel data, including the available number of workers with three

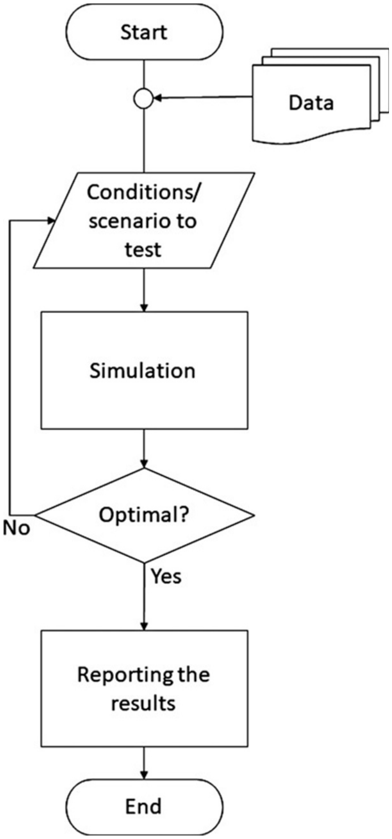

FIG. 9.3.3 A general flowchart for simulation-based optimization process. *Adapted from Masoud, S., et al., Appl. Eng. Agric. (2018).*

different skill levels (defined with processing speed of each task and error rate), the simulation result would generate a report suggesting which workflow design should be used for assembly line and which task should be assigned to each worker (data not shown).

The performance of our simulation-based optimization for worker management (i.e., task allocations and workflow design) was further evaluated by comparing experience-based recommendations made by experts who have a good understanding of the grafting operation [11]. In this study, the optimized worker task allocation generated by the simulation showed greater performance in terms of grafting labor costs compared with the plans suggested by two experts. We believe that this capacity could be further developed into a real-time worker management system considering the dynamic change in worker's availability (weekly or daily) as well as tracking individual workers' learning curves at a plant factory. Such a real-time dynamic optimization system has already been experimented with in the area of industrial factory manufacturing with multiskilled workers assigned to different machines (e.g., Ferjani et al. [12]; Savino et al. [13]).

9.3.2.3 Production Planning and Management

A horticultural technique that we developed to mitigate the weekly fluctuation of labor input associated with the fluctuation in product demand is low temperature storage [14]. By placing plants under a low temperature for a short period of time (e.g., days and weeks), in which plants are kept at a "null" growing mode, grafting timing can be shifted and peak labor input requirements can be lessened. To evaluate the economic feasibility and the actual impact of using low temperature storage, we have applied a simulation approach to optimize the production schedule with a maximum of 2 or 4 weeks of storage for grafted watermelon and tomato plants, respectively, and computed the labor input and resulting costs for selected plant production scenarios. The results demonstrate that, by using low temperature storage, weekly labor needs became relatively stable and the peak time labor costs were reduced by avoiding or mitigating the need of the most expensive yet least experienced type of temporary workers (i.e., migrant workers) and also by allowing a longer work season for unskilled workers to improve their skill set [14]. The impact of low temperature storage was greater for the crop with longer storability (i.e., tomato vs. watermelon) [14], suggesting that environmental control to improve storability is crucial. We illustrate the impact of using low temperature storage on the weekly grafting schedule and number of workers of each type (e.g., skilled permanent workers vs. seasonal temporary workers) to meet a predetermined shipping schedule in Fig. 9.3.4.

A mathematical model to simulate vegetatively propagated transplant production was attempted by Kubota and Kozai [15], where the productivity (number of propagules harvested) and space needs (to keep the stock plants) were computed linearly to examine different methods of propagation applied under different environmental conditions (e.g., light intensity and CO_2 concentration). However, with many real grafting nursery businesses, production planning typically begins with orders (demand) and then considers facility use, labor inputs, and production costs. A combination of such a model to predict the plant growth and development as well as a simulation-based optimization system using industrial and systems engineering will be necessary for developing a next-generation plant production planning system.

9.3.2.4 Supply Chain Analysis

The final example of our approach is a supply chain analysis. This macro-scale analysis uses the concept of "systems in systems", where we aggregate the rather small systems to understand the larger systems' behaviors. Horticultural crop production and its supply change are typically order-driven, due to the perishable product nature (e.g., transplants, leafy greens). Meng et al. [16] examined the impact of a strategy of early order commitment (EOC) in a traditionally order-driven transplant supply chain. The preliminary study using the simulation of the supply chain for transplants could show that the EOC strategy is beneficial to nurseries producing transplants by increasing their profit significantly, while the profit for crop producers who buy transplants increases by delaying the ordering times, due to possible errors in forecasting the demand. When aggregate profit of the supply chain was evaluated, our analysis indicates that the greatest profit gains are from implementing the EOC strategy. This result agrees with a similar supply chain study consisting of retailers, manufacturers, and material suppliers by Zhao et al. [17], which proposed a rebate scheme for supply chain partners to share the gains of practicing EOC.

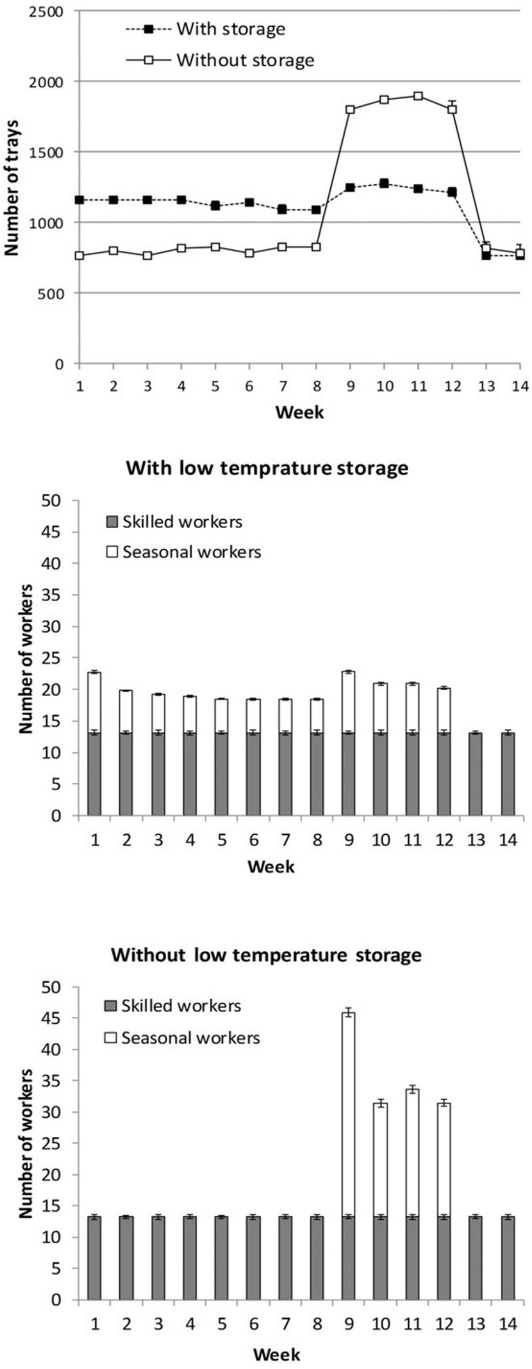

FIG. 9.3.4 Weekly number of seedling trays for grafting, skilled permanent workers, and unskilled temporary seasonal workers needed to meet a selected shipping schedule of grafted plants in a nursery with and without low temperature storage capacity. *Adapted from Kubota, C., et al., PLoS One 12 (2017) e0170614.*

9.3.3 CONCLUSION AND FUTURE PERSPECTIVE

The use of exhaustive computations to effectively analyze and design workflows and productivity with optimized inputs of labor and machinery has been intensively studied and, for some cases, successfully applied in industrial manufacturing processes. Biological systems have much greater uncertainty and complexity, and therefore, are more dynamic, and real-time simulation-based optimizations are desirable. The critical decision process of production management in horticultural crop production is usually on a day-by-day rather than hour-by-hour basis. This timeframe can allow for complex computations needed for decision support throughout the day, possibly via internet-based simulation and optimization services [18] (Fig. 9.3.5). With such an intelligent, dynamic supporting mechanism, the operation of horticultural production systems using plant factories can achieve higher productivity and greater resource efficiency, advancing the sustainability of crop production.

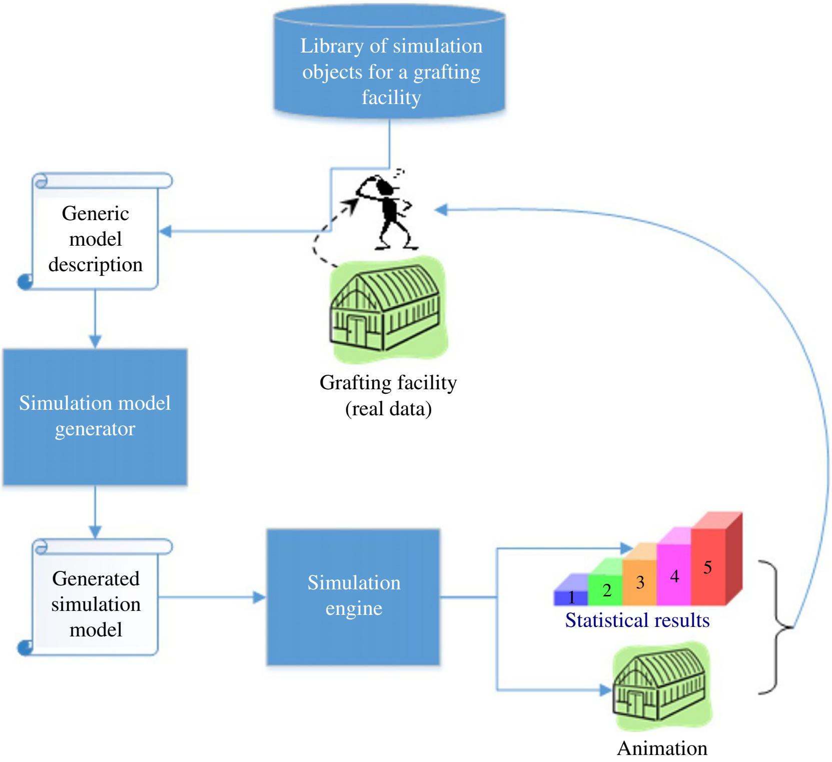
Library of simulation objects for a grafting facility
Generic model description
Simulation model generator
Grafting facility (real data)
Generated simulation model
Simulation engine
1
2
3
4
5
Statistical results
Animation

FIG. 9.3.5 Concept of internet-based simulation and optimization service for grafting labor and other resource management. *Adapted from Son, Y., et al., Comput Indus Eng 45:141–165, 2003; Son, Y., et al., Automatic generation of simulation models from neutral libraries: an example, in: Proceedings of the 2000 Winter Simulation Conference, 10–13 December 2000, IEEE Press, pp. 1558–1567, 2000.*

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CHAPTER

9.4

Plant Factory and Space Development, "Space Farm"

Yoshiaki Kitaya
Osaka Prefecture University, Osaka, Japan

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9.4.1 INTRODUCTION

The US National Aeronautics and Space Administration (NASA) probe, which landed on Mars in 2004, provided evidence for the presence of water on the surface of Mars. This mission was part of a grand plan that would allow the survival of humans on Mars. The presence of water has also been established on the polar region of Earth's Moon. When humans inhabit the Moon and Mars, which are approximately 380,000 km and 78,000,000 km away from Earth, respectively, an environment similar to that of Earth must be created for supporting human life.

Plant Factory using Artificial Light
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Until then, in manned space exploration missions, humans must spend the majority of time within spacecrafts; these life-support devices are indispensable for maintaining human life.

A round-trip manned space flight to Mars takes approximately 17 months excluding length of stay on Mars. According to estimates from NASA, the daily energy requirement (2800 kcal) of one adult male requires 0.62 kg in food dry weight, 3.08 kg of water, 0.84 kg of O_2 necessary for respiration, and 0.11 kg of solid materials, 3.42 kg of water, and 1.0 kg of CO_2 to be discharged (Fig. 9.4.1). The total amount of substances that one person takes into his or her body per day is approximately 4.5 kg, and the total amount of substances discharged each day is the same. The amount of substances such as food, water, and oxygen for supporting life during a 17-month trip to Mars is immense, and it is physically impossible to carry all necessary supplies from Earth. In addition, with the help of current technology, physically carrying the substances required for a 4-day trip to the Moon may cost approximately 1 million dollars/kg, making this trip economically impossible. Therefore, for humans to survive for longer periods on the Moon and Mars, creating a survival environment resembling that on Earth becomes necessary. In addition, in the long-term manned space exploration planned before the migration, a life-support system is indispensable in the spacecraft when humans go out into space.

Animals, including humans, respire and emit CO_2, which plants absorb and fix via photosynthesis for generating O_2. In addition, since animal excrement and nonedible plant parts

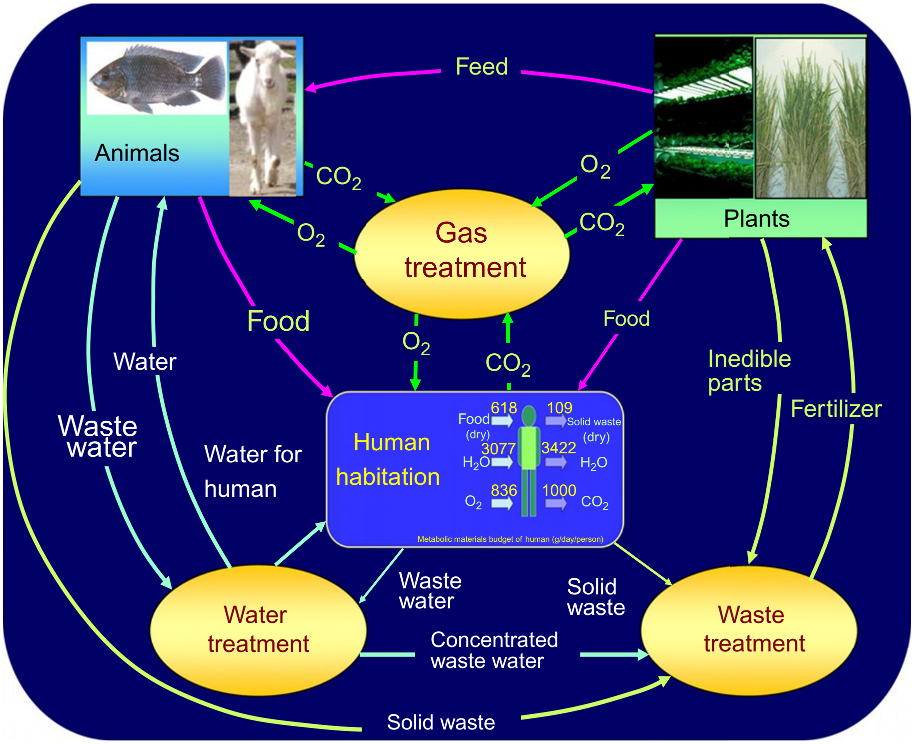


FIG. 9.4.1 Controlled ecological life-support systems with materials recycling in space.

are oxidized and converted into water, CO_2, and other minerals, supply of O_2 for its oxidation and removal of simultaneously generating CO_2 are also dependent on the process of photosynthesis. Furthermore, plants also aid in the absorption and removal of trace gases that are harmful to humans as well as unpleasant odors. Evaporated and transpired water from cultivated plants is condensed and used as drinking water. Moreover, ingesting fresh vegetables and nature contact via living plants can mitigate the physical and mental stress experienced by astronauts. Therefore, in controlled ecological life support systems (CELSS), it is imperative to construct a multifunctional plant cultivation system that includes gas treatment, water treatment, and amenity function, in addition to food production.

Recently, there has been great interest in plant growth and reproduction in space with the increase in the possibility of realizing long-term manned space flight. The life-support of crew in long-term space missions is dependent on the amount of food and atmospheric O_2 produced by plants grown in high densities. The feasibility of achieving long-term manned space missions is entirely dependent on plants in CELSS or space farming that will play crucial roles in food production, CO_2/O_2 conversion, and water purification (Fig. 9.4.1). In space farming, scheduling crop production, obtaining high yields with a rapid turnover rate, and efficiently converting atmospheric CO_2 to O_2 can be established with the precise control of environmental variables.

It is necessary to control the environment for safely and systematically supplying food to people in a space with limited resources and energy and for accurately grasping the behaviors of soundly growing plants. As cultivated plants on the space farms, wheat, soybean, peanuts, sweet potatoes, potatoes, lettuce, carrots, and tomatoes, and as microalga, chlorella, spirulina, and euglena are candidates for space farming because of the nutrients available in their edible parts and the ease of cultivation.

Research and attempts of agricultural systems for space were recently reviewed by Wheeler [1]. From the viewpoint of plant growth as affected by environment, the space environment, including factors such as altered gravity and cosmic rays, may affect the vegetative and reproductive growth of plants in various ways; a few space-flight experiments have attempted to assess the effect of space environment on seed production and the incidence of genetic aberrations [2–4]. Excess supply [5] of CO_2 to plants caused their poor growth in plant-growing facilities in space. Exposures to high ethylene concentrations caused by biogenic activity also negatively affected plant growth and morphology [6,7]. In addition, waterlogging in the rootzone due to inadequate moisture distribution in the rooting substrate may cause a stress under microgravity conditions [8].

The space-specific stress caused the chromosomal anomalies in cells of plants grown in space [9]. Bubenheim et al. [10] reported that pollen from superdwarf wheat grown on the Mir space station contained only one nuclei due to a high level of atmospheric ethylene ($1.2\,\mu mol\,mol^{-1}$), while normal viable pollen is tri-nucleate. Carbon dioxide enrichment and air exchange in plant growth chambers allowed pollen and ovule development to occur normally [11], and the absence of convective air movement caused physiological disorder of pollen development under space-flight conditions [12]. Failure in seed production and the occurrence of genetic aberrations may be attributable to either microgravity, increased cosmic rays in space, or unfavorable growth conditions in the plant-growing facility. However, it remains to be known whether these alterations cause significant changes in the morphology and function of whole plants and reproductive organs when grown in space for a long duration. Long-term experiments conducted in space-flight facilities such as the International Space Station should be able to address these queries.

In space farming, closed plant culture facilities like plant factories are utilized. In such facilities, the estimation of the physical environmental factors (light intensity, light/dark cycle, light wavelength, temperature, humidity, CO_2 concentration) becomes essential in addition to the influence of air movement and root zone environment. The influence of environmental conditions specific to space, such as microgravity and low pressure, must also be considered for establishing environmental control technology for efficient plant production in CELSS.

In this chapter, the influences of major physical environmental factors on the photosynthesis and growth of plants on Earth are explained as commonly controllable environmental factors. Next, the challenges regarding environmental control under microgravity conditions in space are considered.

9.4.2 CONTROL OF PHYSICAL ENVIRONMENT COMMON TO THAT ON EARTH

9.4.2.1 Light

Plants generally release CO_2 by respiration and absorb CO_2 by photosynthesis in the light. The value obtained by subtracting the CO_2 release rate by respiration (respiration rate) from the CO_2 absorption rate by photosynthesis (gross photosynthetic rate), that is, the net CO_2 absorption rate, is termed the net photosynthetic rate, and it has a positive correlation with the growth rate and it increases with increasing light intensity up to the light saturation point. Controllable light environment elements include light intensity, light quality, and lighting length. These elements greatly influence plant growth; light intensity primarily affects the photosynthesis and morphology of the plant, light quality chiefly influences morphology, and the lighting length primarily affects dormancy and flower bud formation.

9.4.2.2 Temperature

Air temperature is generally used as the temperature when discussing the influence of temperature on plant photosynthesis or respiration. However, plant body temperature (or leaf temperature) has a direct effect on the biochemical reactions necessary for plant physiology. For example, the leaf temperature at which the maximum net photosynthetic rate is reached falls in the range of 20–30°C. Leaf temperature increases due to the increase in radiant energy absorbed by the leaves and decreases due to the increase in sensible and latent heat energy transported from the leaves to the air. Therefore, environmental factors (light intensity, temperature, humidity, airflow velocity, etc.) associated with this energy balance influence leaf temperature and eventually influence photosynthesis and growth.

9.4.2.3 Humidity

The relationship between relative humidity and the net photosynthetic rate varies depending on environmental conditions (including airflow velocity), but the net photosynthetic rate is generally maximum at 75%–85% relative humidity. When relative humidity reaches 90%, the net photosynthetic rate decreases, but under high relative humidity (low water vapor pressure deficit [VPD]), water loss due to transpiration is suppressed and water absorption by the root pressure is simultaneously maintained; thus, excess moisture in the leaves is considered to become excessive, and that pressure leads to decrease in the stomatal pore opening. When transpiration is temporarily promoted under low relative humidity (high latitude) and when the water absorption rate of the root cannot catch up with transpiration rate, plants undergo water stress, stomatal pores are closed, and photosynthesis is suppressed.

9.4.2.4 Atmospheric CO_2

Generally, net photosynthetic rate increases with the increase in CO_2 concentration up till the point when it exceeds the CO_2 saturation point. The influence of CO_2 concentration on plant photosynthesis greatly varies depending on other environmental factors such as light intensity and temperature. The CO_2 saturation point increases with increasing light intensity, and the CO_2 compensation point (the CO_2 concentration when the net photosynthetic rate becomes zero) decreases with increasing light intensity. As the CO_2 concentration increases, the influence of leaf temperature on the net photosynthetic rate becomes significant, and the leaf temperature that maximizes the net photosynthetic rate increases. Under a low CO_2 concentration, even if the leaf temperature is raised for enhancing the activity of the enzyme involved in the photosynthetic reaction, the accumulation of photosynthates becomes the limiting factor, so the effect of a higher leaf temperature on the increase in the photosynthetic rate is insignificant.

9.4.2.5 Air Movement

Insufficient air movement around plants increases the resistance to gas diffusion in the leaf boundary layer and thus restricts the photosynthesis and transpiration of plants [13–15], which in turn suppresses plant growth and development. Therefore, the enhancement of gas exchange in leaves and the growth of plants depend on the appropriate control of air movement. Molecules of gaseous substances, such as CO_2 and water vapor, move from high to low concentration sites through turbulent and molecular diffusion. Generally, substance diffusion in air is dominated by turbulent diffusion. When a flat plate is placed parallel to the direction of airflow with uniform velocity distribution, the airflow velocity on the flat plate decreases as it approaches the flat plate surface and it approaches $0\,\mathrm{m\,s^{-1}}$ at the surface of the flat plate. The area where the air velocity decreases near the surface is called the surface boundary layer, and specifically on leaves, the leaf surface boundary layer. The surface boundary layer becomes thicker rearward from the front edge of the flat plate. The vicinity of the leading edge is called the laminar flow area where air flows parallel to the flat surface. Subsequently, the air flows to the rear through the transition region called a turbulent flow region, but the layer in contact with the flat plate surface is in the laminar flow state with a remarkably low flow rate. In the case of a horizontal laminar flow with less turbulence, the turbulent diffusion velocity in the direction perpendicular to the laminar flow is small, and the substance hardly diffuses in that direction; that is, the leaf boundary layer acts as a relatively large resistance against the transport of CO_2 and water vapor between the atmosphere and the leaf surface. This layer becomes thicker with the decrease in the airflow velocity and the increase in the resistance value against gas diffusion.

9.4.2.6 Root Zone Environment

Generally, as the water content in the root zone decreases, the water absorption rate of the roots decreases, the plants undergo water stress, the stomata close, and photosynthesis is suppressed. The influence of the medium's moisture content on the net photosynthetic rate greatly varies depending on other environmental conditions. For example, in case of large VPD, the transpiration rate will be high; therefore, it is necessary to keep the water absorption rate of the roots higher than when the VPD is small for maintaining the moisture content in the leaves. It is thus necessary to maintain sufficient water content in the medium. A similar situation occurs when the light intensity is high. On the contrary, when the water content of the medium becomes excessive, the breathability of the medium deteriorates, and the respiration of roots and microorganisms in the medium causes a decrease in O_2 concentration and an increase in CO_2 concentration in the medium. As a result, the suppression of root respiration and cell membrane water permeability decreases, the water absorption rate of the roots decreases, and photosynthesis is suppressed.

Generally, when O_2 concentration in the root zone becomes 10% (v/v) or less, the net photosynthetic rate dramatically decreases. On the contrary, even if the O_2 concentration in the root zone is high and the CO_2 concentration increases to 1%–2%, the water absorption of the root is suppressed, the plants undergo water stress, and the net photosynthetic rate decreases.

When the temperature of the root zone increases above the optimum value, the respiration rate of the roots increases, the photosynthetic products are depleted, the root zone O_2 concentration decreases, the CO_2 concentration remarkably increases, the root water absorption is suppressed, and photosynthesis is suppressed. When the temperature of the rhizosphere declines from the optimum value, the absorption of the root is inhibited and photosynthesis is also suppressed.

9.4.3 ENVIRONMENTAL VARIABLES INSIDE THE PLANT CANOPY AND CANOPY PHOTOSYNTHESIS

Precise control of the environment for plant growth within a closed chamber is challenging, especially when a large number of plants are grown at a high density in a limited space, which mimics plant factory systems on Earth. Each environmental variable inside the canopy is spatially uneven and is considered to vary with light intensity. Therefore, the values of the variables inside the canopy would differ from those outside the canopy. These characteristics of the intracanopy environment are carefully considered for avoiding poor or uneven growth.

Clarifying the variability of environmental variables inside the canopy as affected by the light intensity is important toward their precise control. Effects of light intensity on the air temperature, water vapor pressure, and CO_2 concentration inside a plant canopy are demonstrated in this section.

Each environmental element inside the plant canopy is spatially uneven and considered to vary according to light intensity. That is, the values would differ from the value that is set for mechanically controlling the environment outside the plant canopy. These characteristics often cause poor or uneven plant growth. The effects of light intensity on the air temperature, water vapor pressure deficit, and CO_2 concentration inside the plant canopy and the possibility for approaching the environmental elements inside the plant canopy to those outside the plant canopy by controlling wind velocity above the plant canopy were reported by Kitaya et al. [16].

When photosynthetic photon flux density [PPFD] was 0.5 mmol m^{-2} s^{-1}, a 2–3°C higher air temperature, 0.6 kPa higher water vapor pressure, and 25–35 μmol mol^{-1} lower CO_2 concentration were observed at heights ranging from 60 to 90 mm above the rooting medium surface inside the plant canopy of young eggplants (mean plant height of 90 mm and leaf area index [LAI] of 6) in comparison with the values 60 mm above the canopy, which were 27°C air temperature, 2.5 kPa water vapor pressure, and 380 μmol mol^{-1} CO_2 concentration (Fig. 9.4.2). Increase in PPFD increased air temperature and water vapor pressure and decreased CO_2 concentration inside the plant canopy. Lower air temperature and higher CO_2 concentration inside the plant canopy were observed at a airflow velocity of 0.3 m s^{-1} than at that of 0.1 m s^{-1} (Fig. 9.4.3).

The environmental elements inside the plant canopy under high light intensity are characterized as higher air temperature, higher vapor pressure, and lower CO_2 concentration than those outside the plant canopy. Appropriate air movement can reduce the differences between the inside and the outside of the plant canopy. Forced air movement is essential for controlling environmental elements around plants, especially in the space where an absence of free convection due to microgravity limits heat/gas exchange between the inside and outside of the plant canopy. There is a possibility of allowing the environmental variables inside the canopy to approach those outside the canopy by controlling the airflow velocity above the canopy.

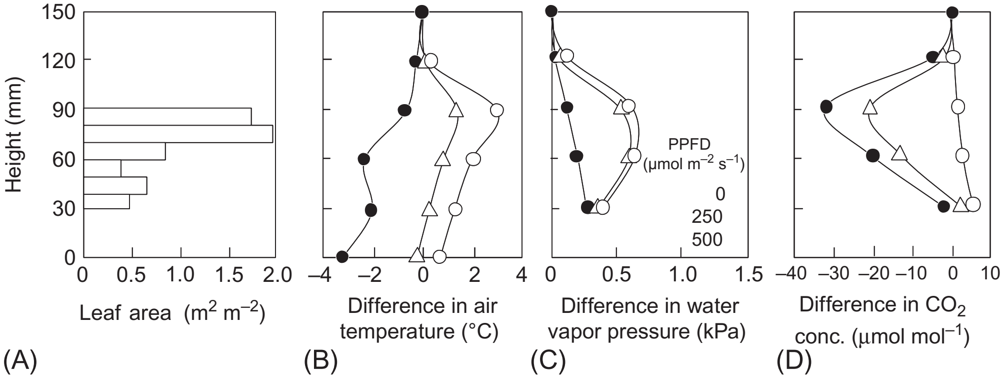
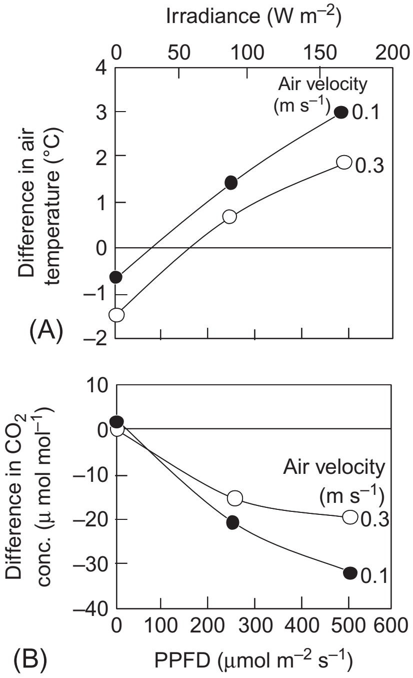


FIG. 9.4.2 Profiles of leaf area (A), air temperature (B), water vapor pressure (C), and CO_2 concentration (D) inside and outside the canopy of eggplant seedlings as affected by PPFD at an airflow velocity of 0.1 m s^{-1}. *From Y. Kitaya, et al., Effects of light intensity and air velocity on air temperature, water vapor pressure and CO_2 concentration inside a plants stand under an artificial lighting condition, Life Support Biosphere Sci. 5 (1998) 199–203.*

FIG. 9.4.3 Effects of PPFD levels on differences in air temperatures (A) and CO_2 concentrations (B) between heights of 90 mm and 150 mm (the reference height) at airflow velocities of 0.1 and 0.3 $m\,s^{-1}$. *From Y. Kitaya, et al., Effects of light intensity and air velocity on air temperature, water vapor pressure and CO_2 concentration inside a plants stand under an artificial lighting condition, Life Support Biosphere Sci, 5 (1998) 199–203.*



Restricted air movement also hinders the gas exchange between plants and the ambient air. When a horizontal air flow system is used, negative effects of restricted air movement on gas exchange are more significant for a plant canopy than for a single leaf because of a significant reduction in the speed of air current inside the canopy [17], especially in a closed plant growth chamber with a large number of plants at a high density even on Earth [18]. Shibuya et al. [19] reported that the evapotranspiration and net photosynthetic rates of a canopy of tomato seedlings under an air velocity of 0.1 $m\,s^{-1}$ were 0.5 and 0.7 times those under 0.6 $m\,s^{-1}$, respectively. The evapotranspiration and net photosynthetic rates of a dwarf-rice plant canopy linearly increased by 0.4 and 0.5 times, respectively, as the air velocity decreased from 0.8 to 0.01 $m\,s^{-1}$. Air movement, therefore, must be properly controlled for enhancing the heat and gas exchanges of plants and, thus, the growth of healthy plants, especially under microgravity conditions. In addition, low air movement induces spatial variations in air temperature, CO_2 concentration, and humidity inside the plant canopy. Poor plant uniformity may, thus, be attributed to variability in the environmental factors around the plants. The precise control of the environment for growing uniform plants in a closed chamber with plants at high density is, therefore, partly dependent on the control of air movement. Retardation in transpiration will cause physiological disorders in leaves called "tipburn," and margins of leaves turn brown and die. The symptoms are majorly caused by the poor translocation of calcium that is usually delivered by the water flow from roots to leaves induced by transpiration.

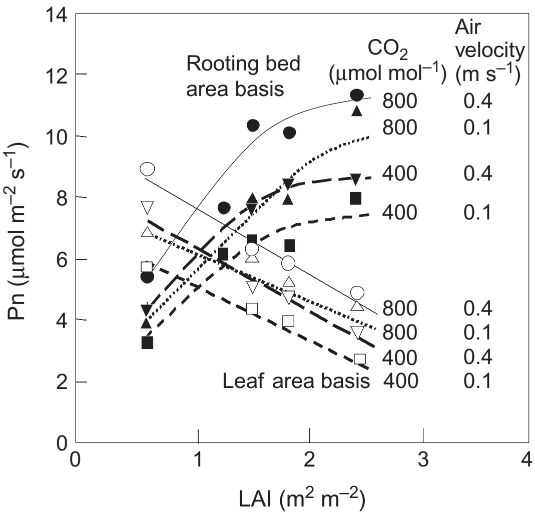


FIG. 9.4.4 Effects of the leaf area index (LAI) on net photosynthetic rates (Pn) based on the rooting bed area (shown with *solid symbols*) and the leaf area (shown with *blank symbols*) of tomato seedlings canopies under different air velocities above the canopies and atmospheric CO_2 concentrations. PPFD: 250 μmol m^{-2} s^{-1}, air temperature: 23°C, RH: 55%, Plant heights: 0.05–0.2 m. *From Y. Kitaya, et al., Effects of air velocity on photosynthesis of plant canopies under elevated CO_2 levels in a plant culture system, Adv. Space Res. 34 (2004) 1466–1469.*

The combined effects of CO_2 concentrations on the net photosynthetic rate of a tomato seedlings canopy are shown in Fig. 9.4.4. The net photosynthetic rate at the air velocity of 0.4 m s^{-1} was 1.3 times than that at 0.1 m s^{-1} under 400 and 800 μmol mol^{-1} CO_2. The net photosynthetic rate under 800 μmol mol^{-1} CO_2 was 1.2 times than that under 400 μmol mol^{-1} at the air velocity ranging from 0.1 to 0.8 m s^{-1}. These results confirmed the importance of controlling air movement for enhancing canopy photosynthesis under elevated CO_2 levels as well as under a normal CO_2 level. In addition, the net photosynthetic rates increased more significantly with increasing CO_2 levels in the plant canopy that had higher LAI and at lower airflow velocity. At an airflow velocity of 0.4 m s^{-1}, the net photosynthetic rates at 800 μmol mol^{-1} CO_2 were 1.2 times and 1.3 times than that at 400 μmol mol^{-1} CO_2 when the LAI was 0.6 and 2.5, respectively. At an airflow velocity of 0.1 m s^{-1}, the net photosynthetic rates at 800 μmol mol^{-1} CO_2 were 1.2 times and 1.4 times than that at 400 μmol mol^{-1} CO_2 when the LAI was 0.6 and 2.5, respectively.

9.4.4 ENVIRONMENTAL CONTROL UNDER MICROGRAVITY CONDITIONS IN SPACE

Regarding the effect of microgravity on plant growth, simulated microgravity experiments are conducted as ground-based experiments utilizing a device called a Klinostat that rotates plants to disturb the direction of gravity. Plant physiological studies on gravitropism using space shuttles have been extensively carried out, and they have shown that plants can grow even under microgravity. Kitaya et al. [20] showed that the growth direction and growth performance of plants can normally be controlled by phototropism, even when the direction of gravity is reversed and the light intensity is not less than 200 μmol m^{-2} s^{-1} (Fig. 9.4.5).

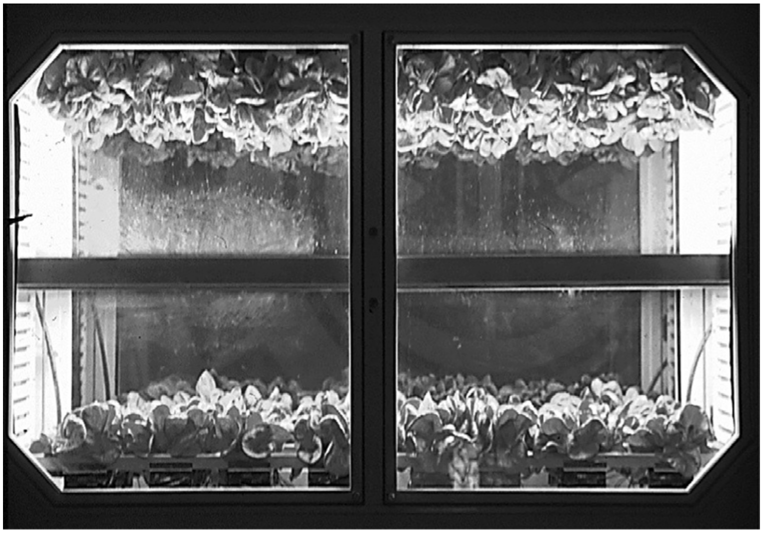


FIG. 9.4.5 Upside down cultivation of lettuce in the ground-based experiment. *From Y. Kitaya, M. Kiyota, T. Imanaka, I. Aiga, Growth of vegetables suspended upside down, Acta Hort. 303 (1992) 79–84.*

Recently, long-term plant cultivation tests at the International Space Station have demonstrated that plants can be grown in long-term space flights.

9.4.4.1 Gas and Heat Exchanges Between Leaves and the Atmosphere under Altered Gravity Conditions

On Earth, free convection can effortlessly occur with uneven temperature distribution. Air movements are induced by convection even in a closed chamber with no forced ventilation system. However, very little free convection would occur under a microgravity condition in space. The limited free convection would reduce plant growth by limiting heat and gas exchanges on plant leaves. Thus, controlling air movement in a closed plant production system is essential for enhancing the heat and gas exchanges between plants and the ambient air, and consequently promoting plant growth.

9.4.4.1.1 Leaf Temperatures as Affected by Gravity

For the clarification of the effects of gravity on heat/gas exchange between plant leaves and the ambient air, the leaf temperatures and net photosynthetic and transpiration rates of plant leaves were evaluated at gravity levels of 0.01, 1.0, 1.5, and 2.0 g for 20 s each during parabolic airplane flights.

The thermal images of barley leaves 20 s after exposure to the gravity levels of 1.0 and 0.01 g showed 1.9°C increase in temperature at the central region in the leaf with decreasing gravity levels (Fig. 9.4.6). The mean leaf surface temperatures of sweet potato and barley decreased by 0.4°C and 0.3°C, respectively, 20 s after gravity levels increased from 1.0 to 2.0 g, and increased by 1.4°C and 1.2°C, respectively, 20 s after gravity levels decreased from 2.0 to 0.01 g at the airflow

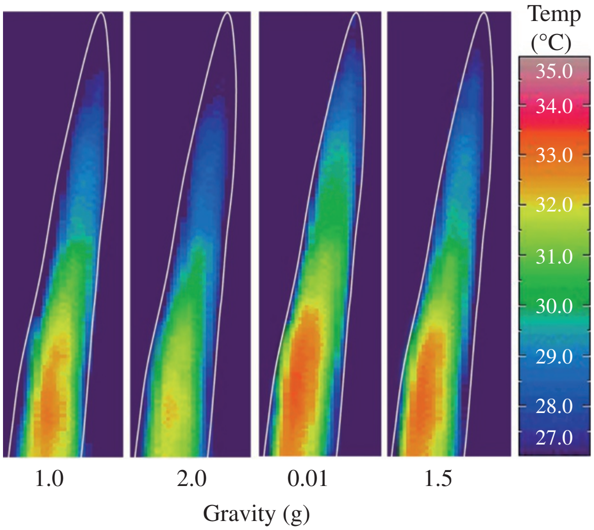


FIG. 9.4.6 Thermal images of the barley leaf at different gravity levels. Ambient air temperature: 28°C, irradiance: 260 W m^{-2}, and airflow velocity: 0.2 m s^{-1}. *From Y. Kitaya, et al., The effects of gravity on surface temperatures of plant leaves, Plant Cell Environ. 26 (2003) 497–503.*

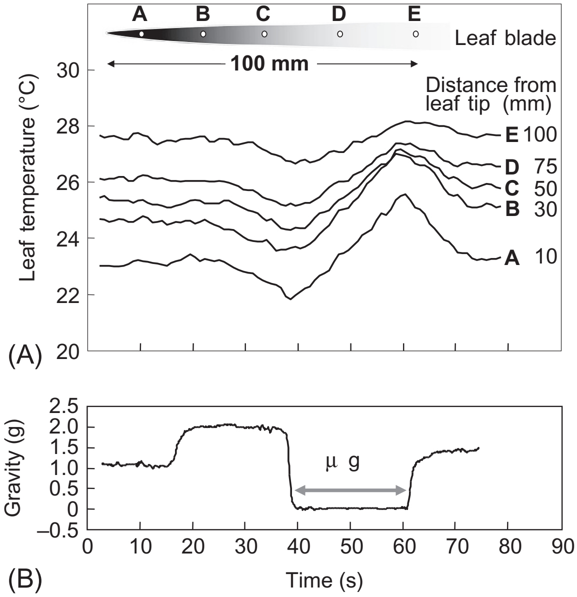
velocity of 0.2 m s^{-1}. The leaf temperature increased by approximately 1.0°C as the gravity levels decreased from 1.0 to 0.01 g. The higher airflow velocity lowered the leaf temperatures. The higher airflow velocity also reduced the surface temperature differences among the different gravity levels.

The increase in temperature was more significant at the narrow regions closer to the leaf tip as the gravity levels decreased. Fig. 9.4.5 shows the close-up thermal images of barley leaves 20 s after exposure to each of the 1.0, 2.0, and 0.01 g gravity levels, respectively. The image shows an increase in the leaf temperature with decreasing gravity levels from 1.0 to 0.01 g and a decrease in the leaf temperature with increase in the gravity levels from 1.0 to 2.0 g. The temperature was higher at the broader region of the leaf. The increase in temperature with decreasing gravity levels was more significant at the narrow region in the leaf blade. Fig. 9.4.7 shows the time courses of the leaf temperatures at five regions with different distances from the tip of the leaf blade corresponding to gravity levels. The temperature decreased for 20 s after gravity levels increased from 1.0 to 2.0 g, and increased for 20 s after gravity levels decreased from 2.0 to 0.01 g at every region.

The temperature variations along the transections on the leaf blades show that the temperature increased with increasing distances from the tip of the leaf (Fig. 9.4.7). The temperature at the region 10 mm from the tip was 3.3°C lower than that at the region 100 mm from the tip at a gravity of 1.0 g. The mean temperatures of five regions were 26.5°C, 24.6°C, and 24.0°C under the gravity levels of 0.01, 1.0, and 2.0 g, respectively. A more significant temperature increase was revealed at the regions closer to the leaf tip as the gravity levels decreased from 1.0 to 0.01 g. The decrease in leaf temperatures tended to be more significant at the regions closer to the leaf tip as the gravity levels increased from 1.0 to 2.0 g.

The reason behind the fact that the increase in temperature was more significant at the narrow regions closer to the leaf tip as the gravity levels decreased seems to be due to the increases in

FIG. 9.4.7 Time courses of the leaf surface temperatures at the central portions along to the representative leaf blade (A) with changing gravity levels (B). Ambient air temperature: 24°C, irradiance: 260 W m^{-2}, and airflow velocity: 0.2 m s^{-1}. *From Y. Kitaya, et al., Heat and gas exchanges between plants and atmosphere under microgravity conditions, Ann. N.Y. Acad. Sci. 1077 (2006) 244–255.*



resistances to water vapor and heat transfer in the leaf boundary layer. The boundary layer resistance is usually less and the surface temperature is lower at the narrower regions at convective situations under the normal gravity conditions. The boundary layer resistance, however, would be mostly constant regardless of the leaf width under the microgravity condition. Therefore, the net increase in temperature with decreasing gravity levels was larger at the narrower regions in the leaf.

9.4.4.1.2 Temperatures of Plant Reproductive Organs as Affected by Gravity

The effect of irradiance levels on the surface temperatures of reproductive organs at different gravity levels is shown in Fig. 9.4.8. The values were determined just prior to the change in gravity. Temperatures of reproductive organs were 1.5–2.5°C lower than the surrounding air temperature in the dark because of the latent heat transfer associated with transpiration in these organs. Temperatures of reproductive organs increased with increasing irradiance levels. The temperatures of the glumes of rice and wheat and anthers of tomato were 4.2°C, 5.9°C, and 5.4°C higher at the irradiance of 150 W m^{-2} than at 0 W m^{-2} at 1.0 g, respectively. The difference in heating trends among the organs may depend on the heat capacity per surface area and the transpiration rate of each organ. The temperature increments of the glumes of rice and wheat and anthers of tomato were 5.5°C, 6.3°C, and 6.0°C, respectively, at 0.01 g, and 3.8°C, 5.7°C, and 5.4°C, respectively, at 2.0 g. The temperature increases of plant reproductive organs as affected by the irradiance level were more significant under a gravity level of 0.01 g and less significant under a 2.0 g gravity level than under a gravity level of 1.0 g.

As the gravity levels decreased from 1.0 to 0.01 g for 20 s, the greater temperature increase was shown in the following order: glumes of rice, anthers of tomato, and glumes of wheat. The temperature increases in relatively small organs, such as the glumes of rice and the

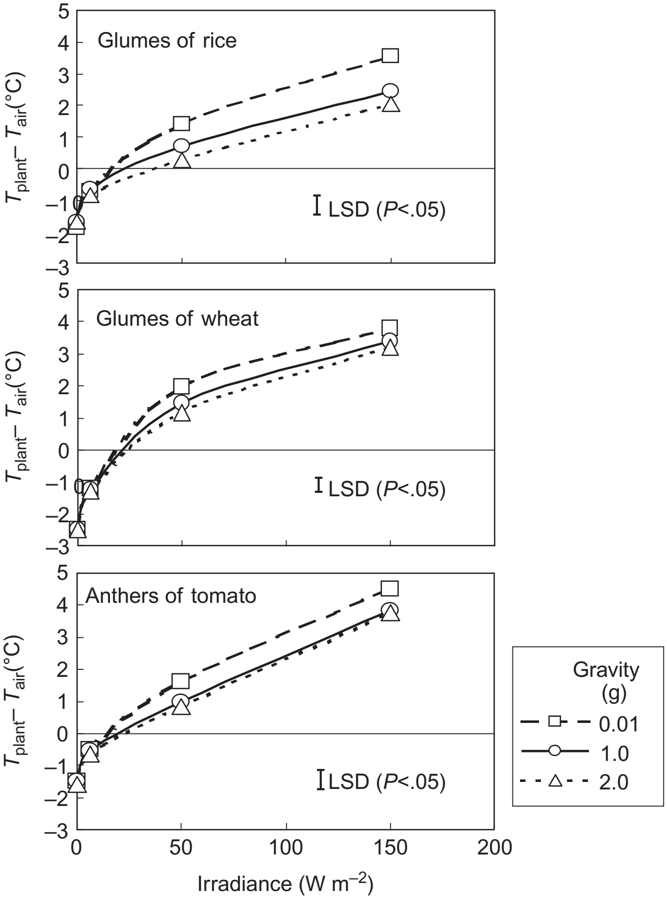


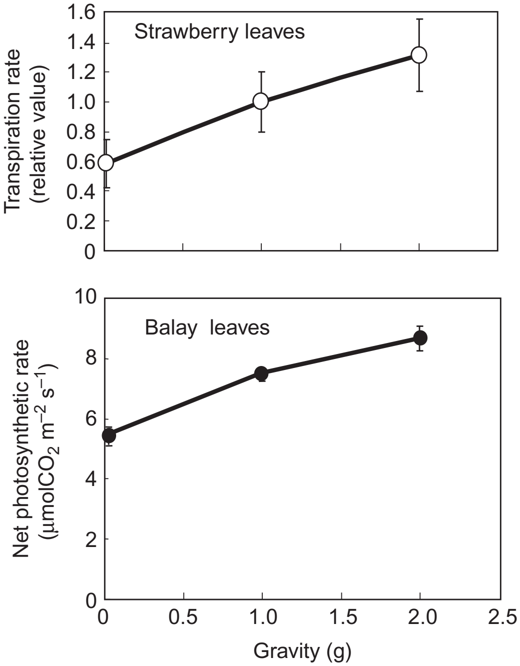
FIG. 9.4.8 Effects of gravity and irradiance levels on temperatures of reproductive organs as shown by differences between organ temperatures (T_{plant}) and ambient air temperature (T_{air}). Ambient air temperature: 31.5°C, airflow velocity: 0.05 m s^{-1}. *From Y. Kitaya, H. Hirai, Thermal situation of plant reproductive organs affected by gravity and light intensity, J. Jpn. Soc. Microgravity Appl. 24(4) (2007) 325–329.*

anthers of tomato, were more significant than in relatively large organs, such as the glumes of wheat, under microgravity conditions. The increase in temperature would be more remarkable under the microgravity condition with less forced airflow.

9.4.4.1.3 Photosynthesis and Transpiration as Affected by Gravity

Gas exchanges between leaves and the ambient air are also retarded by the microgravity condition as well as heat exchange [18, 25]. The net photosynthetic rate was 13% and 20% lesser at a 0.01 g level than at 1.0 and 2.0 g levels, respectively (Fig. 9.4.9). The water vapor transfer from plant leaves (transpiration) and the net photosynthetic rate are suppressed when free air convection is restricted under microgravity conditions (Fig. 9.4.9). Both the increase in the absolute humidity in the vicinity of leaves and the increase in the water vapor resistance on leaves would suppress transpiration under microgravity conditions. Suppressed transpiration would increase temperature rise in plant organs and restrict water and nutrient absorption in roots.

FIG. 9.4.9 Effects of gravity on the Pn of barley leaves 20s after exposure to each gravity level in airplane parabolic flight experiments. *Bars* indicate standard deviations. *From Y. Kitaya, et al., The effect of gravity on surface temperature and net photosynthetic rate of plant leaves, Adv. Space Res. 28 (2001) 659–664; H. Hirai, Y. Kitaya, Effects of gravity on transpiration of plant leaves, Ann. N. Y. Acad. Sci. 1161 (2009) 166–172.*



9.4.4.1.4 *Possible Probrems of Plant Vegetative and Reproductive Growth in Space*

Possible disorders of plant vegetative and reproductive growth in space are summarized in Fig. 9.4.10. Reproductive disorders have been reported under high temperature (30–33°C) stress conditions. Early development and differentiation of wheat anthers were very sensitive to high temperature (30°C day/25°C night) stress causing major alterations in gene expression [22]. The fertilization of bell pepper was sensitive to high temperature (33°C) stress [23]. In my study, the temperatures of reproductive organs rapidly increased to significantly high levels under lighted conditions. This temperature rise could cause reproductive disorders when ambient air temperatures are in the vicinity of 30°C. Arabidopsis and wheat plants grown in space were found to produce and develop flowers, but their flowers produced more sterile seeds than did ground control plants [2–4].

The disorder may have been caused by an increase in the temperatures of reproductive organs, such as anthers and stigmas, due to limited convection under microgravity conditions. Musgrave and Kuang [12] reported that the absence of convective air movement caused a pollen development disorder under space-flight conditions. The increase in temperature would be greater in smaller organs such as anthers and stigmas under microgravity conditions in the absence of convective air movement. Higher radiation and lower air velocity would make the increase in temperature even greater in space. The greater temperature rise in reproductive organs could lead to more fertility impediments.

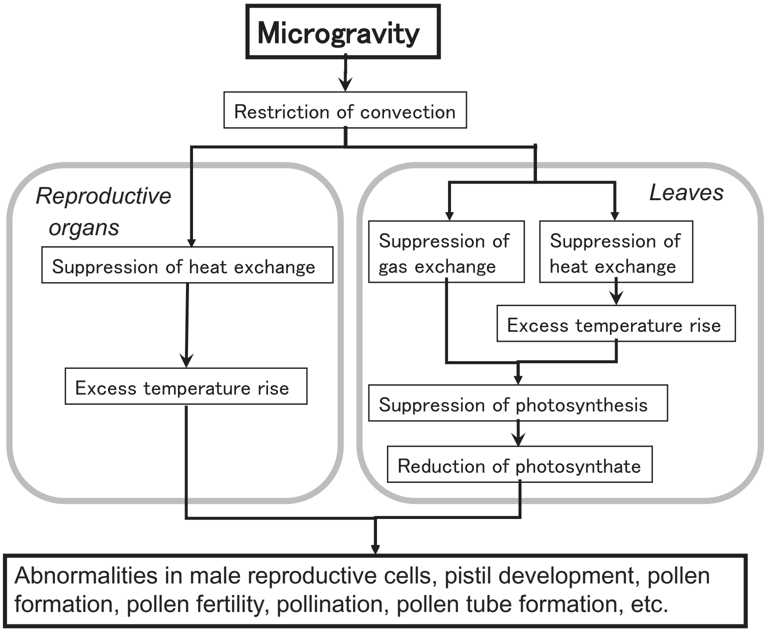

Microgravity
Restriction of convection
Reproductive organs
Suppression of heat exchange
Excess temperature rise
Leaves
Suppression of gas exchange
Suppression of heat exchange
Excess temperature rise
Suppression of photosynthesis
Reduction of photosynthate
Abnormalities in male reproductive cells, pistil development, pollen formation, pollen fertility, pollination, pollen tube formation, etc.

FIG. 9.4.10 Possible plant vegetative and reproductive growth disorders under microgravity conditions.

9.4.5 LOW ATMOSPHERIC PRESSURE IN SPACE

Since the lunar surface is nearly a vacuum (0 atm) and the surface of Mars is 0.2 atm, decompressing inside the space station is considerably easy. Under such a low pressure, the membrane structure of the closed facility can be simplified by lowering the pressure inside the facility. Therefore, the establishment of plant cultivation technology under a low pressure environment is an important issue in space farming. Spinach reportedly grows normally in cultivation under a low pressure of 1/4 of the air pressure on the ground [24]. In addition to low pressure, low gravity is also advantageous for simplifying the structure of the facility due to low weight.

9.4.6 CONCLUDING REMARKS

Plant growth facilities in space require being highly reliable for long durations over multiple plant life cycles with little manual control [21]. Restricted free air convection under microgravity conditions in space would limit plant growth by retarding heat and gas exchanges between leaves and the ambient air.

Proper air movement is essential for promoting plant growth not only in the vegetative growth stages, but also in the reproductive growth stages, especially in space. Considerable effort must be directed toward the development of an adequate environmental control system for enhancing the heat and gas exchanges between plants and the ambient air, thus promoting

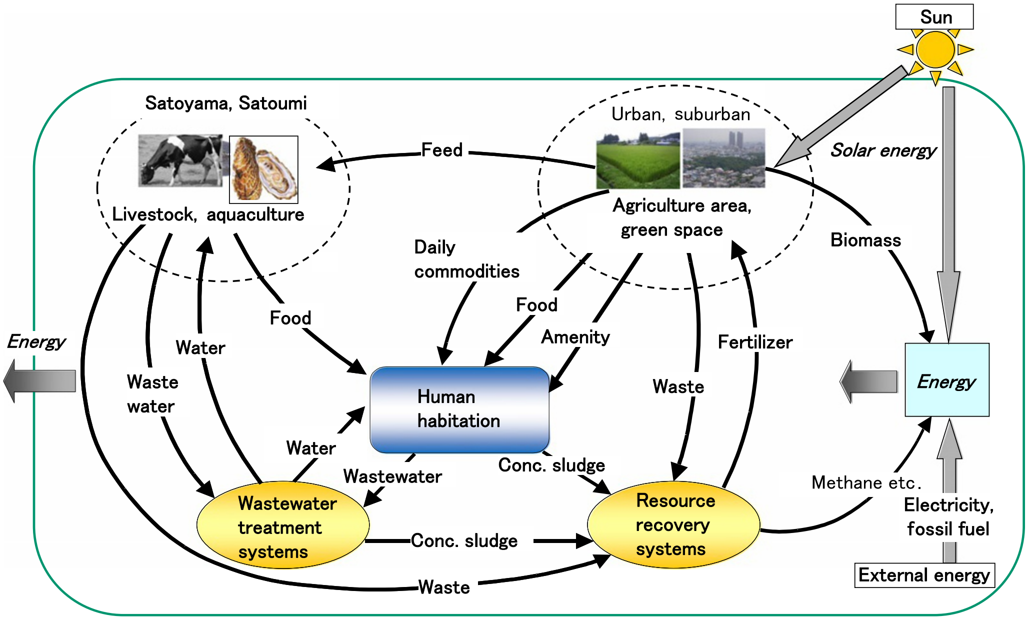


FIG. 9.4.11 Substances and energy flow for reducing environmental impacts in urban areas.

the growth of healthy plants and normal reproduction in CELSS under microgravity conditions in space.

As an example of application of closed plant production in CELSS, plant factory systems can be advanced. For example, plants and mushroom cultivation can be developed [26]. Photosynthetic plants absorb CO_2 and release O_2 in the light period, and mushrooms absorb O_2 and release CO_2 at all times. Plant residues that are discharged from the plant production system can also be used as a medium for mushroom mycelia culture. Furthermore, the concept of CELSS can be developed into urban ecosystems incorporated with agriculture and effective utilization of biomass as shown in Fig. 9.4.11. If we can minimize the amount of input material from outside the system and the amount of input energy other than solar energy, we get closer to a material recycling society that minimizes the load outside the system.

The Earth is an almost complete closed environment in which plants, humans, and other heterotrophs coexist. Therefore, CELSS can be considered as a miniaturization of the material cycling system on Earth. If CELSS centering a plant factory can be constructed, it can contribute not only to the support of long-term manned space activity, but also to be an experimental tool in the analysis of various negative phenomena occurring in abnormal substance circulation and as a solution for the environmental disorders in Earth's ecosystems.

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CHAPTER

10.1

Integration of Artificial Photosynthesis (Photocatalysis) and Natural Photosynthesis for the Environmentally Harmonious Production of H_2 From H_2O Involving Biomass and Vegetables

Yu Horiuchi[*], *Hirokazu Fukuda*[†], *Masaya Matsuoka*[*], *Masakazu Anpo*[*,‡]

[*]Department of Applied Chemistry, Graduate School of Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka, Japan [†]Department of Mechanical Engineering, Graduate School of Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka, Japan [‡]State Key Laboratory of Photocatalysis on Energy and Environment, Fuzhou University, Fuzhou, Fujian, P. R. China

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10.1.1 INTRODUCTION

Recently, solar hydrogen (H_2) production from water has been recognized as one of the most promising technologies to address planetary energy and environmental issues [1–5]. In this technology, readily available and inexhaustible solar energy can be converted and stored as chemical energy, i.e., H_2. When H_2 is used as a fuel to produce electric power through combustion reaction with oxygen, only water is emitted; overall, clean energy cycle can be constructed centering on solar H_2 production. For the industrial realization of this energy cycle, it is indispensable to the development of photocatalytic materials that can efficiently promote H_2 production from water. The pioneering photocatalyst is titanium dioxide (TiO_2), which shows a photosensitization effect in the electrolysis of water into H_2 and O_2 upon irradiating ultraviolet (UV) light, resulting in lowering required external bias, so-called the Honda-Fujishima effect [6]. Thereafter, in view of the fact that UV light accounts for only 3%–5% of solar spectrum, research interest has been directed to designing visible-light-responsive photocatalysts to effectively utilize solar light [7–16]. Various types of visible-light-responsive photocatalysts have been hitherto developed and used in solar H_2 production from pure water; however, their efficiencies are still low for industrial application. On the other hand, the addition of organic compounds into the reaction system is known to improve the rate of the photocatalytic H_2 production since the paired water oxidation reaction involving a difficult four electron process is replaced by simple decomposition reaction of such organic compounds; in other words, organic compounds act as hole scavengers [17]. If biomass and its derivatives that are carbon-neutral feedstocks are used for this purpose, the total reaction system becomes not only efficient but also environmental-friendly, bringing us closer to industrial solar H_2 production. Nevertheless, in the short run, carbon dioxide emission resulted from the decomposition of organic compounds will cause significant adverse environmental effects. In this context, H_2 production systems combined with plant factory has been proposed.

Plant factory is a system to produce plants indoors by artificially mimicking environmental conditions necessary for plant growth. The closed but automated and compact multistage cultivation system enables steady and efficient production of plants independent of weather, climate, and seasons. Moreover, clean environment that requires no pesticide makes the produced plants safe for eating. Therefore, this system has a high degree of expectation for its utilization in urban and desert areas. However, the effective environmental conditions for plant growth, such as CO_2 concentration, light source, irradiation time, and so on, have not been established well, and its survey has become the dominant research trend in this field. In addition, although CO_2 should be supplied to the system in a positive manner because plants ingest CO_2 as essentials for growth, it requires high cost, which makes large scale industrial application difficult.

The integration of these two technologies, solar H_2 production system and plant factory, will compensate for each other's shortcomings, which means that unwanted CO_2 emitted by photocatalytic H_2 production from aqueous media containing biomass or its derivatives can be used for plant growth in plant factory. Moreover, availability of not only unharnessed biomass, but also organic waste products from plant factory as the fuels enables us to construct more eco-friendly system. The overall conceptual diagram is shown in Fig. 10.1.1. In this

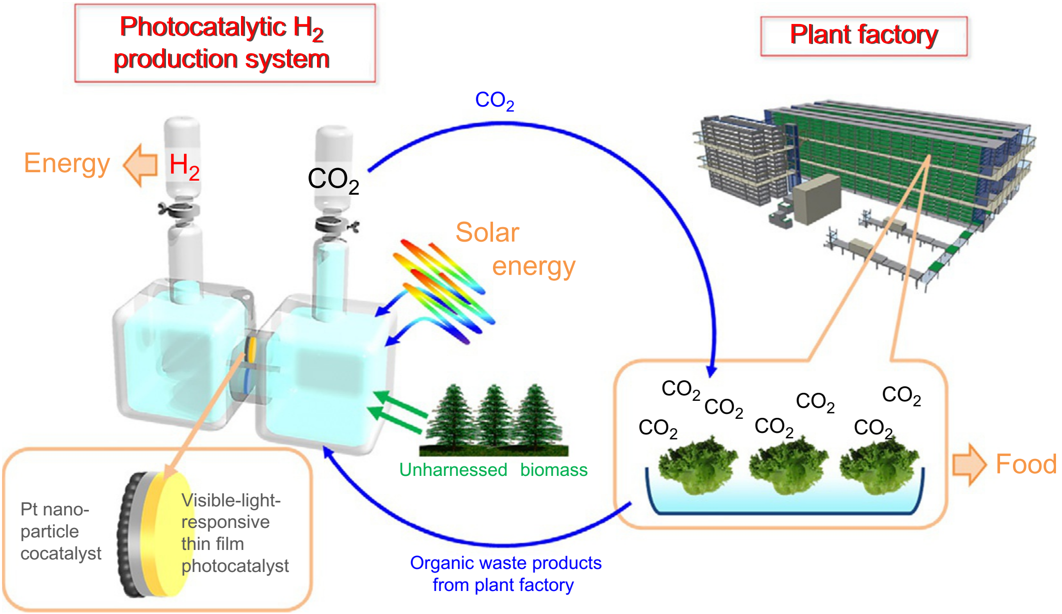

Photocatalytic H_2 production system
Plant factory
CO_2
Energy
H_2
CO_2
Solar energy
Unharnessed biomass
CO_2 CO_2 CO_2 CO_2 CO_2 CO_2 CO_2
Food
Pt nano-particle cocatalyst
Visible-light-responsive thin film photocatalyst
Organic waste products from plant factory

FIG. 10.1.1 Conceptual illustration of a new energy production process based on the integration of photocatalytic solar H_2 production system and plant factory.

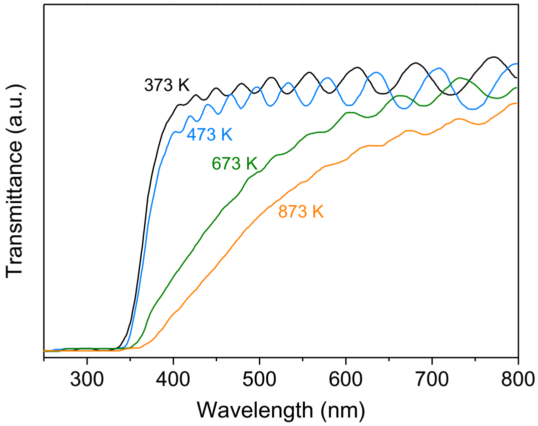
system, it is more preferable to include a device for separate production of H_2 and CO_2 in the solar H_2 production part to avoid the introduction of an additional separation device for H_2/CO_2 mixed gas. The construction of devices based on thin film photocatalysts, such as photoelectrochemical cells and H-type reactors, meets this purpose. The former produces H_2 and CO_2 at the cathode and the anode, respectively, apart from each other. In the latter, CO_2 is produced on the photocatalyst side and H_2 is produced on the reverse side where proton reduction cocatalysts are deposited (see Fig. 10.1.1, the left part).

This chapter spotlights the potential of efficient photocatalytic H_2 production from aqueous media containing various organics catalyzed by a visible-light-responsive TiO_2 thin film photocatalyst and the survey of effective conditions for plant growth, especially CO_2 concentration, in plant factory. Furthermore, a system to generate electrical power in place of H_2 in the presence of biomass derivatives under simulated solar light irradiation, so-called the photofuel cell, is also discussed.

10.1.2 PHOTOCATALYTIC H_2 PRODUCTION USING VISIBLE-LIGHT-RESPONSIVE TiO_2 THIN FILM PHOTOCATALYSTS

Visible-light-responsive TiO_2 thin film photocatalysts can be prepared on various substrates by a radio frequency magnetron sputtering (RF-MS) deposition method using calcined TiO_2 plate as a target material [18]. The optical properties of the deposited TiO_2 thin films are strongly affected by substrate temperatures (T_S) during sputtering. As shown in Fig. 10.1.2, no

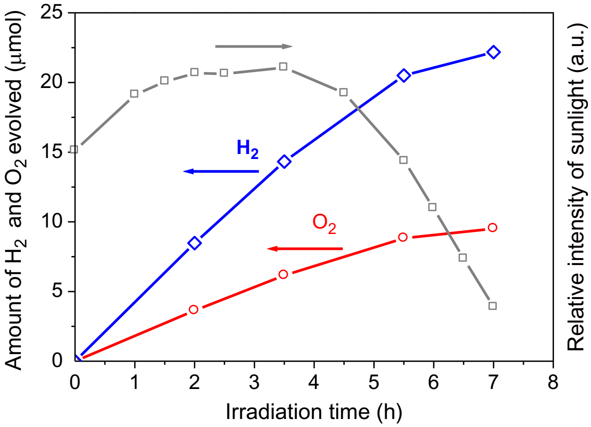
FIG. 10.1.2 UV-vis transmission spectra of TiO_2 thin film photocatalysts prepared by an RF-MS deposition method at different substrate temperatures (T_S=373–873 K).



absorption band above 380 nm was observed for the TiO_2 thin films prepared at T_S=373 and 473 K, while the TiO_2 thin films prepared at T_S=673 and 873 K exhibited distinct visible-light absorption. The origin of these unique optical properties can be explained by their orderly aligned columnar structure with a small amount of oxygen vacancy. The depth profiles of AES measurements demonstrated that the O/Ti atomic ratio of TiO_2 thin films prepared at T_S=873 K decreases gradually from 2.00 at the surface to 1.93 in the deep bulk [18]. The small amount of oxygen vacancy in the TiO_2 lattice is known to cause a distortion of the TiO_2 octahedral unit and weaken the Ti—O bonds, which leads to a reduction of the splitting between the bonding and nonbonding levels [19].

The thus-obtained visible-light-responsive TiO_2 thin films behave as photocatalysts for water splitting to produce H_2 and O_2 under sunlight. The reaction results are shown in Fig. 10.1.3. The reaction was carried out by using an H-type reaction vessel for separate evolution of H_2 and O_2. The visible-light-responsive TiO_2 thin film deposited on a Ti metal substrate, which had Pt nanoparticle cocatalysts on the reverse side, was sandwiched

FIG. 10.1.3 Separate production of H_2 and O_2 from water media by using the visible-light-responsive TiO_2 thin film photocatalyst under concentrated sunlight irradiation.



between two glass containers. The container on the TiO_2 side was filled with NaOH aq. and the other was filled with H_2SO_4 aq. in order to add a small chemical bias to assist the electron transfer from the TiO_2 to Pt side through the metal substrate. Upon the sunlight irradiation to the system, H_2 and O_2 were produced stoichiometrically, suggesting the realization of solar H_2 production. Moreover, even when the system was irradiated with only visible light ($\lambda > 420$ nm) from a Xe lamp equipped with a cut-off filter, the reaction was confirmed to proceed, thanks to the visible-light-responsive nature of the TiO_2 thin film photocatalyst.

Subsequently, the effect of the use of bio-related compounds has been investigated. For this purpose, the methanol was selected as a bio-related compound and added into the reaction solution of the TiO_2 side. As shown in Fig. 10.1.4, the H_2 production rate was significantly enhanced by the addition of methanol. This facilitation of the reaction can be explained by the smooth charge separation due to the efficient consumption of photo-formed holes and the current doubling effect by the resulting organic radicals from organic hole scavengers. The degree of enhancement effect varies according to the kinds of bio-related compounds. Fig. 10.1.5 shows the results of photoelectrochemical measurements for the visible-light-responsive TiO_2 thin film photocatalyst obtained in electrolytes with or without bio-related compounds under visible-light irradiation ($\lambda > 420$ nm). Enhanced photocurrents were observed when not only methanol but various bio-related compounds were added into the electrolyte, indicating the positive role of these organics as hole scavengers. It can be said that smaller compounds and polyols were found to be preferable as the additives to facilitate the reaction.

Following the successful observation of the enhanced H_2 production rate by the addition of bio-related compounds into the reaction system, the possibility of CO_2 emission during photocatalytic H_2 production has been examined. The confirmation of CO_2 emission was performed in a photoelectrochemical H_2 production reaction system using the visible-light-responsive TiO_2 thin film as the photoanode, a Pt cathode, and an electrolyte containing formic acid under UV-vis light irradiation from a Xe lamp at a constant bias of 1.0 V. As shown in Fig. 10.1.6, continuous H_2 and CO_2 production occurred from the beginning of the irradiation period, and the total evolution of H_2 and CO_2 after 6 h irradiation reached 32.9 and

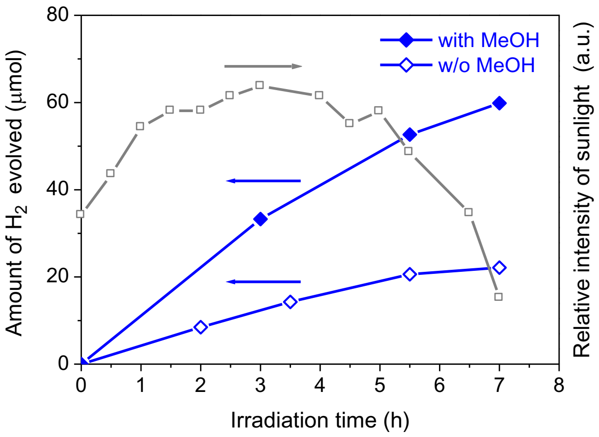


FIG. 10.1.4 Production of H_2 from water media with or without methanol by using the visible-light-responsive TiO_2 thin film photocatalyst under concentrated sunlight irradiation.

FIG. 10.1.5 Photocurrents of the visible-light-responsive TiO_2 thin film photocatalyst observed in electrolytes with or without various bio-related compounds under visible-light irradiation ($\lambda > 420$ nm).

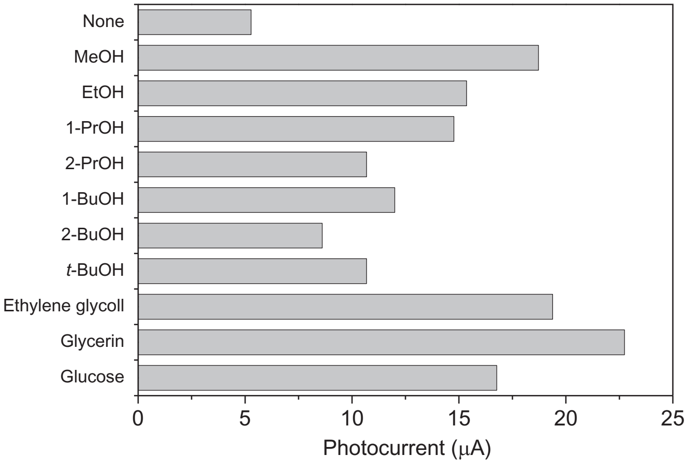
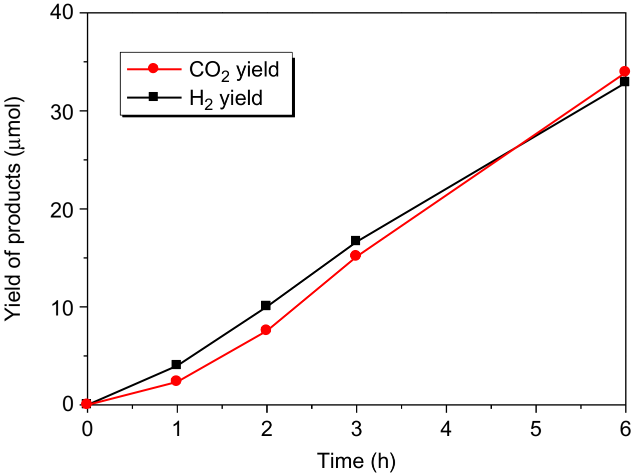


FIG. 10.1.6 Time course plots of photoelectrochemical H_2 production from an electrolyte containing formic acid under UV-vis light irradiation at a constant bias of 1.0 V.



33.9 μmol, respectively. Thus, bio-related compounds added into the H_2 production system were found to serve a dual role as hole scavenger and CO_2 source. All these findings relating to the use of bio-related compounds indicate the effectiveness of biomass and its derivatives as additives for combining system of efficient H_2 production and plant growth.

10.1.3 APPLICATIONS OF VISIBLE-LIGHT-RESPONSIVE TiO_2 THIN FILMS FOR PHOTOFUEL CELLS

The results emanating from the above photocurrent measurements stimulate our interests in the solar energy conversion not only to H_2, but also to electricity. The photoelectrocatalytic system to produce electricity by employing various biomass and bio-related compounds as fuels was developed by Kaneko et al. and named photofuel cells (PFCs) [20]. The device is composed of a photoanode, a cathode, and an electrolyte containing various biomass and bio-related compounds as fuels. Upon light irradiation, biomass and bio-related compounds were oxidized by photo-formed holes at the photoanode, while photo-formed electrons transfer to the cathode through the external circuit and reduce oxygen there. The one important advance of PFCs has been made by constructing a separate-type system [21]. The separation of PFCs into two compartments for photoanode and cathode sides enables to use respective two different electrolytes. The electrolyte for the photoanode side contains various biomass and bio-related compounds as fuels, while an iodine ion redox couples (I_3^-/I^-), which is typically used in dye-sensitized solar cells for efficient electron transfers in the system, is added into the other. The photovoltaic performances under simulated solar light irradiation of separate-type PFCs (SPFCs) using the above-discussed visible-light-responsive TiO_2 thin film photocatalyst as photoanodes are summarized in Fig. 10.1.7. The addition of I_3^-/I^- redox couples into the catholyte effectively improved their photovoltaic performances. Moreover, interestingly, the same performance was observed between SPFCs using a carbon cathode and a Pt cathode in the presence I_3^-/I^- redox couples. It can be said that a cost-efficient carbon is available as an alternative to Pt for the cathode by constructing the separate-type system. The positive effect of the addition of various biomass derivatives was also observed in the SPFCs (Fig. 10.1.7B). Among those explored in that study, when glycerin was used as fuel, the SPFC exhibited the highest performance with an open circuit voltage (V_{OC}) of 0.72 V and a short-circuit current densities (J_{OC}) of 0.57 mA cm^{-2}. These results suggest the possibility of biomass utilization in SPFCs, and eventually, the positive combination of plant factory based on CO_2 formed by biomass decomposition at the photoanodes.

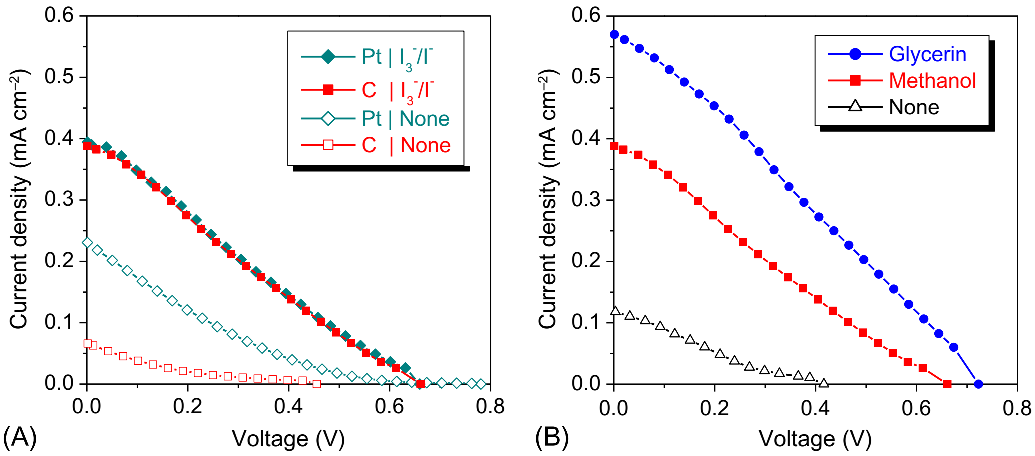


FIG. 10.1.7 I–V curves of SPFCs based on the visible-light-responsive TiO_2 thin film observed under simulated solar light irradiation. The SPFCs were consisted of (A) Pt or carbon cathode, catholyte with or without iodine redox couples, and anolyte with methanol and (B) carbon cathode, catholyte with iodine redox couples, and anolyte with or without biomass derivatives.

10.1.4 THE SURVEY OF EFFECTIVE CONDITIONS FOR PLANT GROWTH IN PLANT FACTORY

In a large scale plant factory (5000 lettuces day^{-1}), the fixation rate of CO_2 was estimated as 67 kg day^{-1} under the standard condition including 1000 μmol mol^{-1} CO_2 concentration, which represents about two times the quantity in earth atmosphere. To explore more effective ingestion of CO_2 by plants, experiments under higher CO_2 concentrations were required.

The growth promoting effect under high CO_2 concentration conditions was examined for three plants (lettuce, perilla, and rice). Lettuce is used as a model plant in plant factories, and perilla and rice as models of medicinal and grain plants, respectively. The plants were cultivated under 500, 1000, 1500, 2000, and 3000 μmol mol^{-1} CO_2 concentrations. Then, the fresh weights of the aerial part in three plants were measured at 14 and 21 days after planting. As a cultivation system, a hydroponic culture system with fluorescent lamps in a cleanroom was used (Fig. 10.1.8). Fig. 10.1.8A shows the cultivation process in each plant under 1500 μmol mol^{-1} CO_2 concentration, which is three times the concentration of the atmosphere. A physiological disorder, called chip-burn, was observed on the seventh, eighth, and ninth leaves from the inside of lettuce (Fig. 10.1.8C and D), even though the chip-burn does not occur under standard condition in plant factories.

Fig. 10.1.9 shows the relationship between CO_2 concentration and growth. In lettuce, the fresh weight under high CO_2 concentration (3000 μmol mol^{-1}) was more than twice the one under the standard concentration (1000 μmol mol^{-1}) (Fig. 10.1.9A). In general, it is known that the photosynthesis rate is saturated when the CO_2 concentration in the intercellular reaches 1000 μmol mol^{-1} (Fig. 10.1.9B), but our results show that lettuce growth has a higher saturation point. On the other hand, the quality index, which represents the incidence of chip-burn, decreased with increasing CO_2 concentration (Fig. 10.1.9A).

In comparison among three plants, lettuce showed the largest growth rate, indicating lettuce has the highest CO_2 fixation ability (Fig. 10.1.10A). It was found that perilla and rice possess, respectively, 70% and 20% of CO_2 fixation ability of lettuce. CO_2 fertilization is indispensable in plant factories, but it was found that growth suppression occurs when the CO_2 concentration increases up to 2000 μmol mol^{-1} (Fig. 10.1.10B). In particular, in lettuce, chip-burn was observed under both conditions of 1500 and 2000 μmol mol^{-1}. From these results, it was also clarified that the high concentration of CO_2 causes problems of growth inhibition and physiological disorder depending on the cultivar. Using several environmental controlling technologies including application of air flow, these problems will be solved in the future.

10.1.5 SUMMARY

In this chapter, the feasibility of a novel renewable energy production system involving solar H_2 production, biomass utilization, and plant factory was described. In the solar H_2 production, the increase in the reaction rate was achieved by the addition of biomass derivatives into the reaction solution, even though the emission of CO_2 occurred simultaneously through the decomposition of biomass derivatives. On the other hand, in plant factory,

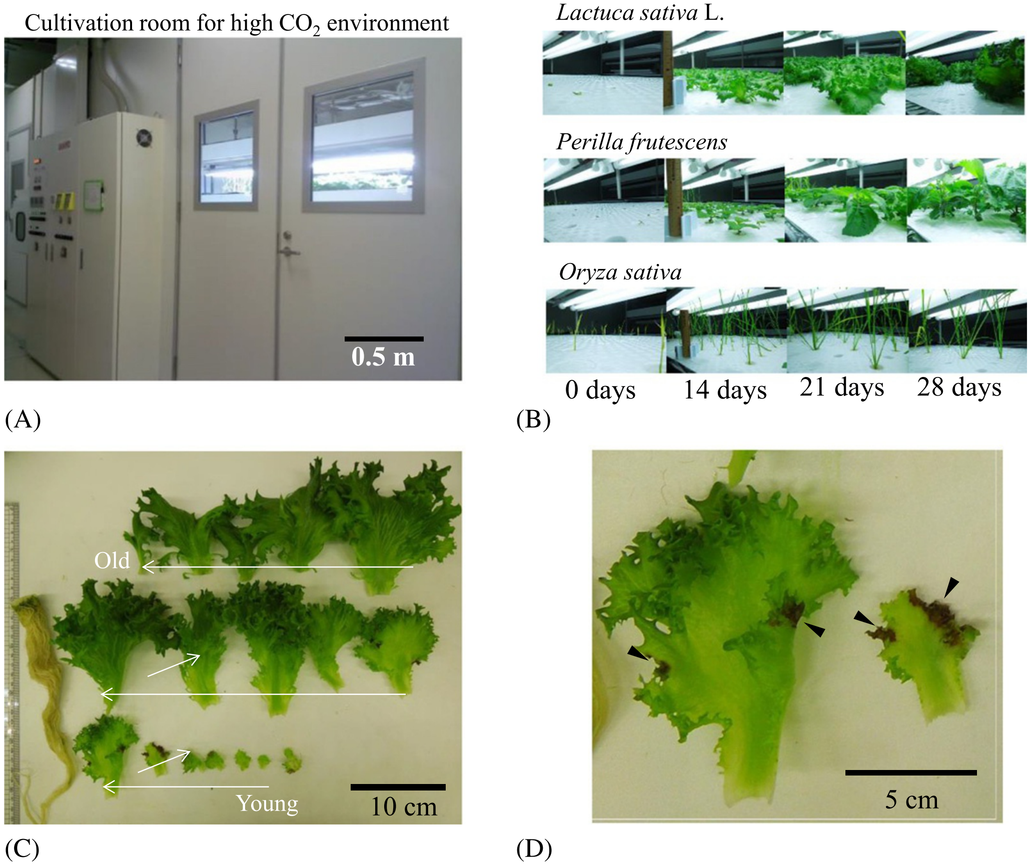


FIG. 10.1.8 Cultivations under high CO_2 concentrations. (A) A clean room for cultivation under high CO_2 concentrations, which are controllable up to 4000 μmol mol^{-1}. (B) Snapshots of lettuce (*Lactuca sativa* L.), perilla (*Perilla frutescens*), and rice (*Oryza sativa*) at different cultivation times. (C) Lettuce cultivated for 3 weeks under 1500 μmol mol^{-1} CO_2 concentration. (D) A physiological disorder, Chip-burn, on the young leaves.

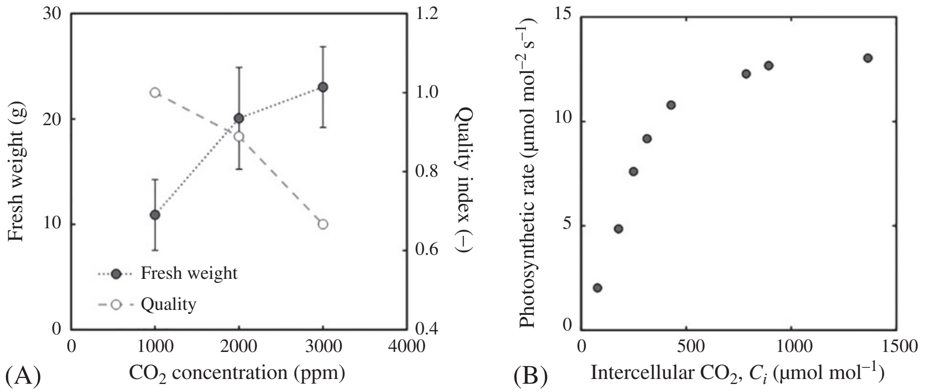


FIG. 10.1.9 Relationship between CO_2 concentration and growth in lettuce. (A) Fresh weight and quality index as a function of CO_2 concentration. The quality (quality index) represents the incidence of chip-burn. $N = 12–18$. (B) Relationship between the intercellular CO_2 concentration and photosynthetic rate. *Data from G.D. Farquhar, et al., Planta 149 (1980) 78.*

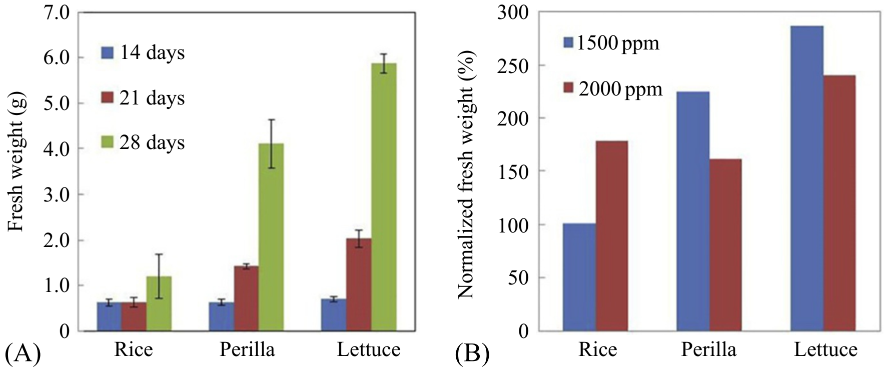


FIG. 10.1.10 (A) Fresh weight of the aerial parts in each plant under 1500 μmol mol^{-1} CO_2 concentration. $N=4$–21. (B) Growth rate of each plant under high CO_2 concentrations. The normalized fresh weight was calculated as the fresh weight of the aerial part on 21 days cultivation divided from that of the plants on 14 days cultivation.

the growth-promoting effect for various plants was observed under high CO_2 concentration conditions, as such, it was found that CO_2 emitted by solar H_2 production in the presence of biomass derivatives is not unfavorable but useful when these two systems are integrated. Also, solar H_2 production could be replaced by solar electric power generation using photofuel cell. This rational and environmentally harmonious integration of solar H_2 production and plant factory will open up new era in our society.

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Plant Factory Using Artificial Light

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Dr. Masakazu Anpo is Professor Emeritus at Osaka Prefecture University (OPU). He is also a Special Honor Professor and International Advisor at Fuzhou University. At its beginning and for several years after, he was Vice President/Executive Director and Director of the Research and Development Center for the Plant Factory of OPU. He is a pioneer in the study of photochemical reactions on solid surfaces including catalysts, having published many books including Photochemistry on Solid Surfaces (Elsevier). Dr. Anpo has received many awards and served as an editor-in-chief/on editorial boards for numerous international journals. His research interests include the design of visible light-responsive TiO2 thin film photocatalysts, g-C3N4 and h-BCN photocatalysts, and highly active single-site metal oxide catalysts constructed within zeolite frameworks and meso-porous materials, including their applications for safer environments and clean energy.

Dr. Hirokazu Fukuda is a professor at Osaka Prefecture University in Course of Bio-Production Engineering Systems, Department of Mechanical Engineering in Graduate School of Engineering. He is also affiliated with the Research and Development Center for Plant Factories, Osaka Prefecture University. His research has focused on the development of plant diagnosis systems, using modeling and bioinformatics to find a way to increase productivity in plant factories. His unique prediction model and bioinformatics for biological clocks have been installed in commercial plant factories. Currently, he is studying instability in plant production caused by the nonlinearity of plant environmental responses.

Dr. Teruo Wada is an associate professor at Osaka Prefecture University in Course in Plant Production Science, Division of Applied Life Sciences in Graduate School of Life and Environmental Sciences. He is also affiliated with the Research and Development Center for Plant Factories, Osaka Prefecture University. His research has focused on year-round production of high-value vegetables through hydroponic systems in greenhouses and plant factories. More specifically, he studies technologies to control mineral composition in nutrient solutions and optimize growth environments for vegetables. Recently, he is working on aquaponics applied to lettuce and loach, and postharvest technologies for vegetables and fruits using hydrogen water.

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